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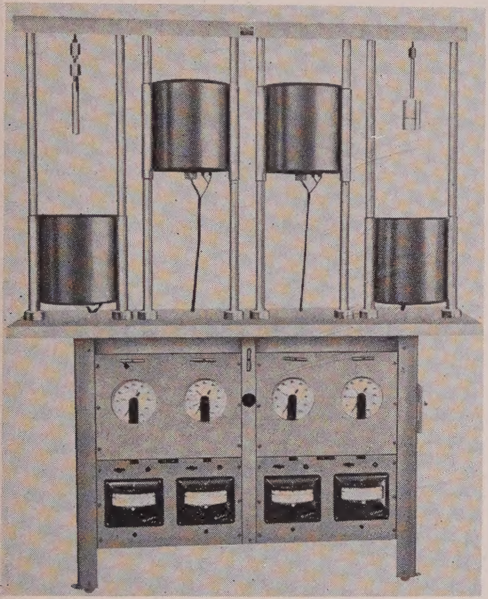

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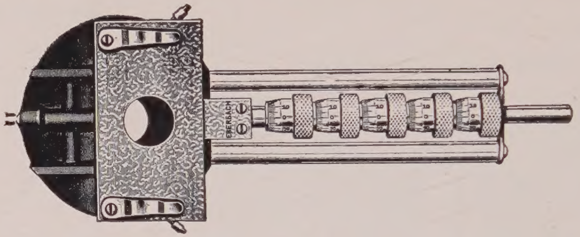

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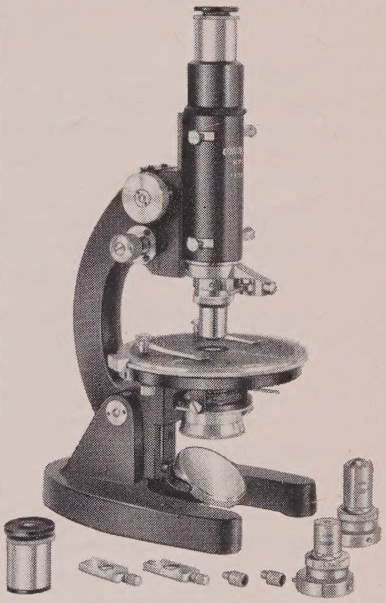

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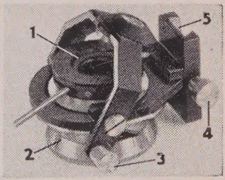

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THE AMERICAN MINERALOGIST

JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

Vol. 46 MARCH–APRIL, 1961 Nos. 3 and 4 (Part 1)

CRESTMORE, PAST AND PRESENT*

JOSEPH MURDOCH, *University of California at Los Angeles, Los Angeles, California.*

When it came to be my turn, as retiring president of the Mineralogical Society of America, to deliver the customary parting address, it seemed quite natural to turn for my subject to Crestmore, since I have been in close touch with this remarkable mineral deposit for over thirty years. During this time, I have made repeated trips to this locality, which is a little west of Riverside, California, and only about sixty miles from my headquarters at U.C.L.A. These trips have been made alone or with uccessive classes of students from the University, and I feel that it has been, and still is, year in and year out, one of the most consistently profitable and rewarding sources of interesting mineralogical material anywhere in the world. Thinking back over these visits, I bring to mind one in particular which might well serve to "point a moral and adorn a ale." It was several years ago, when I encountered a small group of visitors to the quarry, among whom was a youngster of boy scout age, who was prowling in impatient fashion over the fragments of talus while his elders were busily collecting specimens. He was making most scornful remarks about "nothin' but ole quarry rock," just about the time that I was making an exciting find close by. To the boy, and to most of he general public I suppose, Crestmore is "just a quarry," since there is nothing particularly showy there apart from the beautifully blue calcite. But to a mineralogist, it is one of the seven wonders of the world, and a place worth all the "blood, sweat and tears" involved in what my students sometimes defined as "beating on boulders." After all, when you break open a rock, the exposed surface is something that has never before been seen by human eye, and occasionally that sight is highly rewarding. This is particularly so if the break happens to occur along a ein in which there is a cavity, for on the walls of this there may be a coating of beautifully developed crystals. The only trouble with a place ke Crestmore is that with continuous excavation of rock, and only inter-

---

* Address of the retiring President of the Mineralogical Society of America at the 41st annual meeting of the Society at Denver, Colorado, Nov. 1, 1960.

TABLE 1. NEW MINERALS FOUND AT CRESTMORE

Wilkeite	1914	Merwinite	1921	Parawollastonite	1935
Riversideite	1917	Foshagite	1925	Ellestadite	1937
Plazolite	1920	Tilleyite	1933	Nekoite	1955

NEW, BUT AS YET UNNAMED

Mineral Z	1953	Woodford's group	1940–41
10 Å hydrate	1959	(Minerals C, D, F, J, L, M and Q)	
Mg borate	1959		

mittent visits possible, many potential specimens go through the works and disappear. As Eakle commented, "the cement contains the calcined remains of many beautiful, rare, and perhaps new minerals." The title I have selected, "Crestmore, Past and Present," should perhaps have been extended by adding the word "future," because the locality seems as inexhaustible as the miraculous pitcher of Philemon and Baucis. I can vouch for the fact that in all my visits to Crestmore over this period of more than thirty years, I have practically never drawn a blank. I would take a class there, firmly resolved not to do any collecting, and then, in the course of showing a typical occurrence to a student, would encounter a specimen which was different, and warranted further examination in the laboratory. So much for the resolution! Of course, the cream has been skimmed, and most finds are of secondary interest, but not all, even now. The record of new minerals, for instance, with their dates of discovery as shown in Table 1, indicates that the end is not yet in sight, and there seems to be no reason to suppose that continued careful observation will not continue to produce results.

HISTORY

The earliest activity at Crestmore was the quarrying of limestone for lime-burning. This began some undetermined time before 1907, from some pits at the site of the present Commercial quarry on the east side of Sky Blue Hill. The old bins and lime works were in existence up to about 1940. They appear in a picture taken about 1928, shown in Fig. *2a*.

A panorama taken from the west in about 1906 is shown in Fig. 1*a*. Perhaps if one of you is an old car fan he can date this picture from the automobile. This shows the original land surface, with Sky Blue Hill at the left and Chino Hill to the right. Quarrying for cement rock was started on the west side, mainly on Chino Hill, about 1907, and a plant was erected in 1909. At the same time, the Commercial quarry was being operated for road material as well as limestone, as was probably the high level North Star quarry on the northerly slope of Sky Blue Hill. This, as well as the workings on the west side, is shown in Fig. 1*b* probably taken in 1915 or before. Figure 1*c*, taken in March, 1917 from a slightly different angle, shows further progress in excavation. The record is somewhat vague here, since one statement is made that the high level quarry was the North Star, and that the Lone Star was started about 1917 between this and the Commercial quarry. It seems likely that this intermediate quarry is the one now called the Wet Weather quarry, and that the name Lone Star was applied to the North Star.

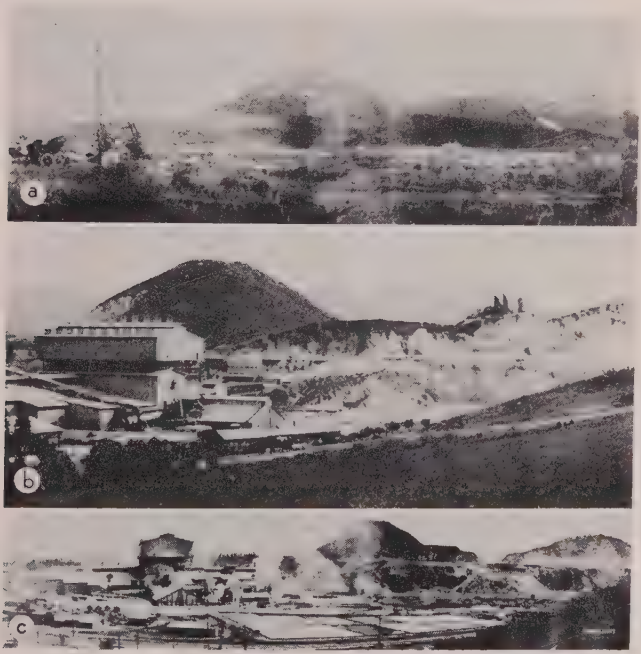

FIG. 1. Early views of Crestmore. (a) About 1907; (b) 1915; (c) 1917.

Two pictures taken from the air in 1928 show the general quarry pattern at that time. The first one (Fig. 2*a*), from the east, shows the old Commercial quarry face and in the foreground, the old lime kiln structures. This also shows the increased extent of quarrying on Chino Hill and its extension to the north. The second picture, (Fig. 2*b*) from the opposite direction, shows as well the high Lone Star quarry, the greatly deepened Wet Weather quarry, and a bit of the floor of the Commercial quarry.

In 1927 a shaft was started for underground mining, and excavation ultimately resulted in caving in of the surface and development of a glory hole between Chino and Sky Blue Hills. This is shown in a photograph taken in 1935 which shows the headframe of this shaft, and the beginning of a steep face on the west side of Sky Blue Hill (Fig. 3*a*). Mine and open pit were both worked until about 1930, but from that date to 1939 the only production was from the mine. Late in 1940 some limestone was taken out on the east side, from the platform of the now abandoned Commercial quarry, and at this time the old lime kiln structures were removed. Then again, in 1946 and 1947 the Commercial quarry floor was cut into from the south, the excavation joining up with the 1940 workings, and forming the 910 foot level from which very extensive collections have been made in recent years. Since this time, and up to the present, all production has been from the underground workings, which now are down to a depth of some 550 feet below the surface. Figure 3*b* shows the present Commercial quarry face and the 910 foot level.

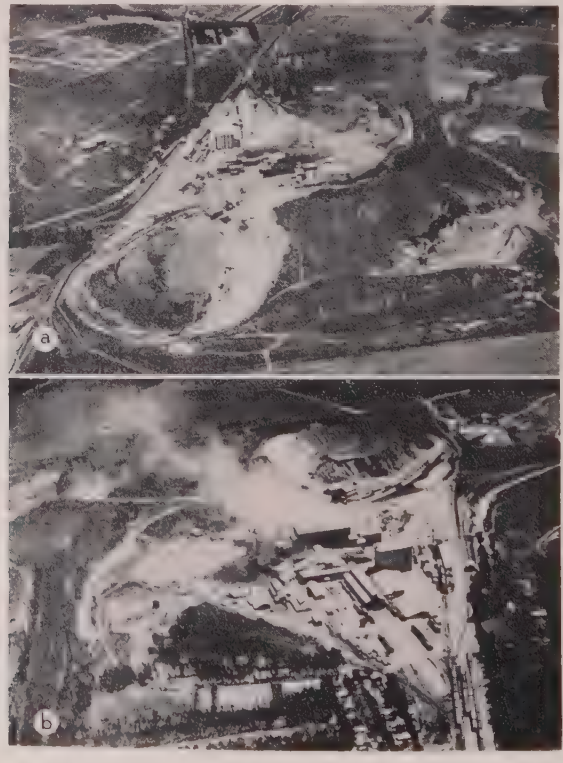

FIG. 2. Crestmore in 1928. (a) View from East, showing old Commercial quarry face, and old lime kiln structures. (b) View from West, showing the high Lone Star quarry and greatly deepened Wet Weather quarry.

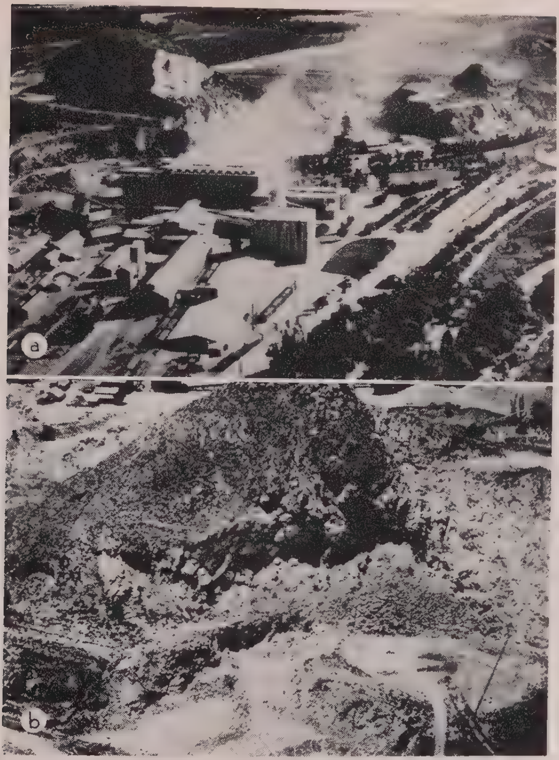

FIG. 3. (a) Crestmore in 1935; (b) 1956 (By permission, Geological Society of America).

GEOLOGY

The oldest rocks of the area are metasediments, in part crystalline, vith some quartzite and other metamorphic types. These may be Misissippian or Triassic in age—there is no conclusive evidence, although omparisons have been made with the Mississippian Furnace limestone, nd with the Triassic Bedford Canyon formation.

These rocks have been extensively invaded by quartz diorite which epresents the northerly extension of the San Diego batholithic complex. Erosion has lowered the surface to the point where only patches of the netamorphics have been preserved, embedded in a matrix of the quartz liorite as roof pendants or "curtains." The Crestmore area represents ne of these patches, which consists mainly of crystalline limestones or narbles, and a lesser amount of quartzite. The limestones are repreented by two roughly lenticular bodies which dip in an easterly direcion, as shown in Fig. 4. The upper, or Sky Blue limestone is about 500 feet in thickness, and is separated from the lower, slightly thinner Chino limestone, by an intrusive tongue of the quartz diorite. The Chino is in a somewhat irregular and wrinkled syncline, while the overlying Blue Sky has been somewhat bulged up by the intrusion of quartz monzonite porphyry which forms irregular or pipelike intrusions in the Blue Sky limestone or between it and the quartz diorite. At this time, or slightly later, there have also been intrusions of various pegmatites, mostly small.

The limestones are quite similar, consisting of layers of predazzite alternating with pure limestone, and with some layers of magnesium-poor rock. The Sky Blue series included some very large masses of almost pure blue calcite, and both it and the Chino are quite coarsely crystalline, although not solid enough to be marble such as could be used in building.

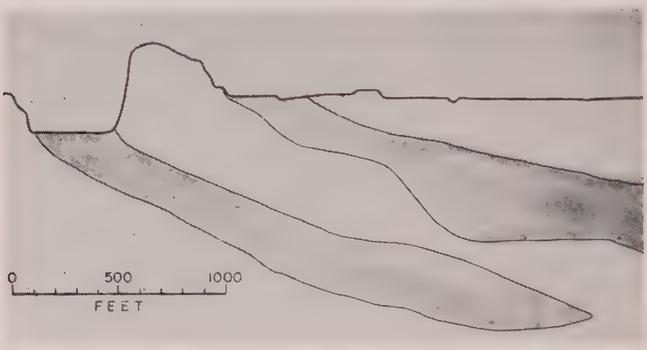

FIG. 4. Lenticular bodies of crystalline limestone at Crestmore. Upper—Sky Blue; Lower—Chino.

Contact effects of the quartz diorite are expressed by the presence of a relatively narrow, simple contact zone, presumably by the development, in its hotter stages, of the abundant periclase originally present in the predazzite, and by coarsening of the crystalline texture of the limestones.

Contact effects of the quartz monzonite porphyry are much more pronounced, and involve silication of thick zones in the limestone, perhaps development of the blue color in some of the calcite, and formation of a mixed or hybrid rock by absorption of limestone by the intrusive magma. The thick masses of contact rock show a zonal distribution of minerals from the intrusive contact to the untouched limestone, and it is in this region that many of the unusual minerals appear.

MINERALS

A great deal has been written about Crestmore and its minerals, but this afternoon I propose to bring only the more important portions to your attention. The initial papers were purely descriptive, and this term could probably be applied to most, but a few of the later ones have been more concerned with mineralogic history, origins and relationships. Before considering these you may be interested in a few statistics: The total number of named and identified minerals to date is 137, with an additional dozen or so which are so far unidentified, many of which are probably new. Of the named minerals, nine are new, as shown in Table I. Six of these have not yet been found elsewhere, and two more, riversideite and nekoite in only one or two other localities. I have listed parawollastonite as new, for it was on material from Crestmore that Peacock (1935) first recognized its monoclinic character, and suggested that the name wollastonite be used for the more common triclinic form. This puts Crestmore on a par with the two other great contact metamorphic assemblages Franklin, New Jersey, and Långban, Sweden, each with essentially the same number of recognized species.

The attention of mineralogists was drawn to Crestmore as a contact metamorphic assemblage of considerable interest by A. S. Eakle (1914), at a meeting of the Geological Society of America. The abstract of this paper listed only a few of the minerals observed, including the rare mineral xanthophyllite, but was followed by a later, more complete presentation. In this year wilkeite, the first of the new minerals, was described by Eakle and Rogers (1914) and named in honor of the late R. M. Wilke, ardent mineral collector and dealer of Palo Alto. This was a good one to start off with, since it is a mineral of the apatite group with the unprecedented number of four acid radicals—phosphate, silicate, sulphate, carbonate. In this paper, they also mention the mineral okenite, which they describe as appearing as an alteration product of wilkeite.

A more complete paper by Eakle (1917) lists a total of 56 species, and describes two new minerals. These are crestmoreite and riversideite, both hydrous calcium silicates but with different percentages of water. Crestmoreite was described as an alteration product of wilkeite, taking the place of the earlier-named okenite. The mineral has since been shown to be tobermorite, always occurring with some residual wilkeite. Riversideite, occurring principally as white fibers interstitial to idocrase grains, and as veins in massive idocrase, is a doubtful but probably valid species. In this paper also, an occurrence of white needle-like grains was described as okenite, but this material has recently been shown by *x*-ray study to be nekoite, a new mineral.

In the next two years another seven species appeared, among them the rare mineral periclase (Rogers 1918), whose presence had been postulated as the original of the brucite granules, but which had not been found before. It appears as very occasional cores inside nests of brucite in the predazzite rock, confirming the earlier diagnosis. Here also plazolite, another new mineral, was described by Foshag (1920).

From 1921 1925 ten additional species were found, and of these three were new. Merwinite was described and named by Larsen and Foshag (1921). In the same year, Eakle (1921) determined jurupaite, which has since been considered to be a magnesium-rich xonotlite. A new mineral, foshagite, was described, also by Eakle (1925). It was later considered to be identical with hillebrandite (Berman 1937) but more recent work (Heller and Taylor 1956) has shown the validity of this material as a separate species.

During the period 1933–1937 twelve additions were made to the list, among them three more new species. The first of these was tilleyite, named by Larsen and Dunham (1933). Then Peacock (1935) determined the triclinic symmetry of one type of wollastonite crystals described by Eakle from Crestmore. He proposed that the name wollastonite be applied to this modification, and that the far less common monoclinic variety be called parawollastonite. Some of these truly monoclinic crystals are found among Eakle's Crestmore wollastonites, so that both modifications are present here. Then D. McConnell (1937) observed and named ellestadite, a wilkeite-like mineral with little or no phosphate radical present.

Rather extensive papers by Woodford and his associates (Woodford et al. 1941, Woodford 1943) added twenty-eight recognized species, most of them by their own observations. Besides these, they list at least eight unnamed species, some of them probably new, besides some others which have since been identified. These papers devote considerable attention to distribution of minerals throughout the quarries, and make incidental comments on the origin of several.

There is no published record of any additions to the list until 1949, when the mineral perovskite was noted, by the present author, Murdoch (1949), but a number of new occurrences were observed over the previous six years, in specimens from his personal collection and in material sent him by private collectors.

In the period 1951 55 eleven names were added, and among these was the new compound nekoite determined by Gard and Taylor (1955) from material Eakle had called okenite. Several of the observed species are rare, among them afwillite, scawtite, and bultfonteinite. Prior to these years, one probably new mineral was observed and partially described by the writer, and tentatively called mineral Z, but the results were not published, in absence of a reliable analysis. Qualitative tests indicated that this was a hydrated silicate carbonate of calcium.

Recently C. W. Burnham (1959) published a very complete paper on the detailed geology and paragenesis of minerals on Crestmore, and I have drawn freely on this in outlining the sequence of events and the characteristic features of the locality.

During the autumn and winter of 1959–60, I have had the privilege of working in the Harvard laboratory on an extensive collection of Crestmore material made by Col. C. M. Jenni. At the same time Alden Carpenter, a graduate student, has been working on his own collection of Crestmore specimens at the same place. The results of study here are by no means complete, but in the course of routine examination an additional eight named species have been added, including the rare minerals ettringite, szaibelyite, and huntite. In addition, a number of definite species have been observed which are so far not identified, and some of which are surely new.

The presence of such a great variety of minerals is due to the rather complex geologic history of the occurrence. This produced a fortunate combination of conditions which permitted the development of many uncommon compounds as well as of the usual species. There were a number of factors involved in this history, which started with the metamorphism of the original sediments, included the crystallization of the various igneous intrusions, continued with their successive contact effects, and ended with surface weathering and oxidation. The early, presumably regional, metamorphism of the sediments, and the final weathering, produced few minerals and no very interesting ones. Intrusion and crystallization of the igneous intrusives produced the normal suites of rock-forming minerals, and in the case of the quartz diorite, resulted in the development of a thin, normal contact zone with grossularite garnet, epidote and wollastonite. Early stages of the intrusion of this rock may well have been responsible for the formation of the original abundant periclase in the magnesium rich layers of the limestone. With dropping temperatures late hydrothermal agencies from the same source may have hydrated most of this periclase to the nests of foliated brucite that we see now. At the same time, some of the purer limestone may have received its blue color. There is as yet no adequate explanation for this color. The pegmatites may have been injected at about this time, but seemed to be responsible for very little mineralogic change.

The somewhat later intrusion of the quartz monzonite porphyry is responsible for the development of an extensive aureole of contact rock, some of it completely silicated. Burnham (1959) has observed a definite zoning in this aureole, starting next to the igneous rock with grossularite as the principal mineral, accompanied by minor wollastonite and diopside. The next zone is almost entirely idocrase, and the outermost mainly monticellite with a rather long list of minor constituents, such as chondrodite, clinohumite, merwinite, tilleyite, etc. This zoning shows a successive decrease in the ratio $Si+Al+Fe/Ca+Mg$ with increasing distance from the intrusive, and indicated that these elements were added metasomatically to an originally essentially pure limestone.

These zones are not always well defined, and are complicated by the irregular form of the intrusives. Further, we may find variations in them to produce local masses made up of idocrase-diopside-grossularite-spinel, monticellite-idocrase-wollastonite-diopside, or spurrite-merwinite-gehlenite. These may be solid silicate masses or may be interspersed with irregular patches of coarsely crystalline, often bright blue, calcite. In these calcite patches we sometimes find metallic sulphides, galena, bornite, chalcopyrite, disseminated in droplike pellets. Some of these are perfectly fresh, while others are altered to secondary carbonates or oxides. In a few cases the galena is surrounded in the neighboring matrix by minerals like wulfenite or mimetite.

Some of the massive garnet-wollastonite zone is composed of very fine, sugary grossularite, and fracture surfaces in this mass are often characterized by the presence of foshagite in "slip-fiber" form, like asbestos, or painted over with a thin coating of a brilliant blue mineral so far unidentified. This has tentatively been called mineral Y, and some of its characteristics determined, but not enough pure material is so far available for final determination though it appears to be a copper bearing calcium silicate hydrate. Mineral Y may occur alone on a surface, or in combination with foshagite, or less often as pellet-like aggregates of thin blades occurring in calcite just like the metallic sulphides.

The massive monticellite rock, brown in color, also is cut by narrow veins, rarely over one-eighth to one-quarter inch wide, filled with fibrous or platy white minerals. Usually these are massive, but occasionally small cavities allow the formation of crystals. Some of this vein filling is thaumasite, showing a cross fiber pattern and in the rare open spaces well developed terminated crystals. Much of it, however, is a platy mineral which I observed several years ago, and have tentatively called mineral Z. This occurs locally in the grossularite rock and the merwinite-spurrite rock as well as here, and normally appears as botryoidal groups of clustered blades. Rarely it develops freely, forming multiple or even more rarely, single thin crystals, reasonably suitable for single-crystal *x*-ray study. These crystals are so thin as to be practically invisible when viewed on edge, so that goniometric measurements are impossible. Optical properties, *x*-ray powder pattern, unit-cell dimensions and symmetry correspond closely to one of the calcium silicate hydrates (14 Å) described by Heller and Taylor (1956) and the qualitative chemical composition is essentially the same. A satisfactory chemical analysis had not been possible until last winter, when a more abundant supply became available from the Jenni and Carpenter collections at Harvard. Analysis of this material showed the presence of several per cent of B_2O_3 and CO_2, although these do not appear to affect the powder pattern. With the availability of this analysis, a reasonably complete description and naming of this mineral is in process. It has been suggested that it is somewhat similar in composition to Daubree's plombièrite, and so should be given this name, but his material was a gel, rather poorly described, and this is crystalline. In my opinion mineral Z is a definite and different substance, and deserves species rank and a name of its own. Some of the white crusts, in the merwinite-spurrite rock particularly, are very like mineral Z in appearance and gross chemical composition, but give a distinctly different *x*-ray powder pattern, corresponding to another of the calcium silicate hydrates of Heller and Taylor (with a prominent line at 10 Å), and appears to be free from admixture. The chemical analysis shows a different proportion of CaO to SiO_2 from mineral Z, so this also should be considered a mineral species.

In the spurrite-merwinite rocks, many of the veins are quite different from those just described, and are characterized by the presence of scawtite (sometimes accompanied by mineral Z), or afwillite (often with ettringite). Scawtite and afwillite are ordinarily in small, but well formed crystals. Ettringite is locally abundant, as tiny hexagonal prisms or as larger crystal grains without external form, and in the latter case often peppered through in poikelitic fashion, by afwillite. Analysis of the ettringite showed the presence of considerable Al_2O_3, SiO_2 and CO_2, and single photographs gave a unit cell with twice the *a* dimension of the published value for ettringite. Accordingly, this material was considered to be an allied but new mineral, and given the name woodfordite by Murdoch (1958). However, re-examination of the unit cell dimensions of ettringite showed the calculation of the *a* axis to be in error. The true value is double, thus making the cell size identical with woodfordite. It was then considered that the difference in composition was not enough to warrant making a new species, and that woodfordite should be considered as a variant of ettringite.

This group of vein minerals should probably be referred to a very late hydrothermal stage in the contact process. Further from the contact, with less complete silication, the invading minerals take the form of small grains disseminated in the calcite. These grains range in shape from smoothly rounded pellets to nearly perfect crystals. The commoner minerals involved are idocrase, diopside, wilkeite (less commonly with development of crystal faces), spinel, a colorless to gray monticellite (practically never showing crystal outlines). More rarely we find chondrodite, perovskite, and magnesioferrite.

In this sparsely mineralized region, wilkeite is usually more or less completely altered to the mineral called crestmoreite by Eakle. This has been shown to be tobermorite, practically all with residual wilkeite, even down to the submicroscopic state. The enveloping calcite is apparently entirely unaltered, but here again, as in the case of scawtite, afwillite, and mineral Z, the alteration is probably late hydrothermal in character.

In the Sky Blue limestone just below Burnham's locality N on the 910′ level of the Commercial quarry, there are various stringers of pegmatitic material carrying gray diopside, quartz, orthoclase and sporadic merwinite. Closely associated with these is a mass of mangesium-rich limestone carrying several borate minerals. One of these is ludwigite, occurring in small well formed black prismatic crystals. Another is a hydrous magnesium borate which appears to be a new species. It occurs as single prismatic individuals or clusters of prisms, colorless but usually with minute black flecks arranged in parallel position. Crystal outlines are usually poor, although good faces occur in the prism zone. The matrix is a mixture of rather coarse grains of calcite and dolomite. Late, probably hydrothermal action has reduced many of the borate crystals to white powdery szaibelyite and an unidentified magnesium carbonate. Chemical analysis shows hydroxyl as well as water of crystallization and a ratio MgO to BO_2 of five to one. A detailed description of this mineral is in progress. Closely accompanying this borate, we find feathery sprays of another unknown mineral, probably a borate, altered to white szaibelyite. This material needs further study.

Locally, notably in material from the Lone Star or Wet Weather quarries, galena and sphalerite are relatively abundant, and appear with their oxidation products anglesite and cerussite, hemimorphite and smithsonite. A perceptible cadmium content of the sphalerite is revealed by rare coatings of bright orange greenockite. After the closing down of these quarries, a good deal of this sort of material was available for a while from a dump ridge along the eastern boundary of the company's property. This dump unfortunately is now buried under sand from an extensive stripping operation.

I have tried to give you my impression of Crestmore as I have known it, a wonderful collecting ground and a place worthy of the enthusiasm of any ardent mineralogist. In closing, I wish to express my deep appreciation of the favors and courtesies extended to me over the years, by the Riverside Cement Company and its staff. Not only have they supplied me with invaluable pictures and information, but during all my visits to Crestmore I have had the most pleasant personal relationships in all my contacts there.

References

(In chronological order)

Eakle, A. S. (1914) Some contact metamorphic minerals in crystalline limestone at Crestmore, near Riverside, California: (*Abstr*) *Bull Geol. Soc. Am.* **25,** 125.

——— and Rogers, A. F. (1914) Wilkeite, a new mineral of the apatite group, and okenite, its alteration product, from Southern California: *Am. Jour. Sci.* (4) **37,** 262–267.

——— (1917) Minerals associated with crystalline limestone at Crestmore, Riverside County, California: *Calif. Univ. Dept. Geol. Sci. Bull* **10,** 327–360.

Rogers, A. F. (1918) An American occurrence of periclase and its bearing on the origin and history of calcite-brucite rocks: *Am. Jour. Sci.* **46,** 581–586.

Foshag, W. F. (1920) Plazolite, a new mineral: *Am. Mineral.* **5,** 183–185.

Larsen, E. S. and Foshag, W. F. (1921) Merwinite, a new calcium-magnesium orthosilicate from Crestmore, California: *Am. Mineral.* **6,** 143–148.

Eakle, A. S. (1921) Jurupaite, a new mineral: *Am. Mineral.* **6,** 107–109.

——— (1925) Foshasite, a new silicate from Crestmore, California: *Am. Mineral.* **12,** 97–99.

Vigfussen, V. A. (1931) The hydrated calcium silicates: I. the system $CaO\text{-}SiO_2\text{-}H_2O$. II. Hillebrandite and Foshagite: *Am. Jour. Sci.* (5) **21,** 67–78.

Larsen, E. S. and Dunham, K. C., Tilleyite (1933) a new mineral from the contact zone at Crestmore, California: *Am. Mineral.* **18,** 469–473.

Peacock, M. A. (1935) On Wollastonite and Parawollastonite: *Am. Jour. Sci.* **30,** 495–529.

McConnell, D. (1937) The substitution of SiO_4- and SO_4-groups for PO_4-groups in the apatite structure: ellestadite, the end member: *Am. Mineral.* **22,** 977–986.

Woodford, A. O., Crippen, R. A. and Garner, K. B. (1941) Section across Commercial Quarry, Crestmore, California: *Am. Mineral.* **26,** 351–381.

Woodford, A. O. (1943) Crestmore Minerals: *Calif. Jour. Mines and Geology Rept.* **XXXIX,** 333–365.

Murdoch, J. (1949) (abstr) Perovskite from California: *Bull Geol. Soc. Am.* **60,** 1911. (1951) *Am. Mineral.* **36,** 573–580. .

Gard, J. A. and Taylor, H. F. W. (1956) Okenite and Nekoite (a new mineral): *Mineral Mag.* **31,** 5–20.

Murdoch, J. (1958) Woodfordite, a new mineral from Crestmore, California: (abstr) *Bull Geol. Soc. Am.* **69,** 1620–21.

Burnham, C. W. (1959) Contact metamorphism of magnesian limestones at Crestmore, California: *Bull Geol. Soc. Am.* **70,** 879–919.

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VULCANITE, A NEW COPPER TELLURIDE FROM COLORADO, WITH NOTES ON CERTAIN ASSOCIATED MINERALS

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Abstract

A copper telluride found in specimens from the Good Hope Mine, Vulcan, Colorado, has been determined to be a new mineral. It is named vulcanite, from the locality of the mine.

Vulcanite forms light bronze to yellow-bronze aggregates of prismatic or bladelike to irregular grains of metallic luster. One prominent cleavage and one less prominent are probably pinacoidal. Twinning nearly at 45° to the prominent cleavage is shown. Hardness is between 1 and 2; specific gravity is indeterminate owing to impurities. In polished section, vulcanite is strongly bireflectant (reflectivity in white light is *ca*. 36.0% to 58.5%), varying from bright yellow to yellow-white to medium blue-gray. Extinction is parallel to cleavage and the long axes of laths. Rotation sense is (−) relative to the prominent cleavage. Anisotropism is very strong; polarization colors are yellow white, grayish yellow-white, yellow-orange, gray. Phase difference in white light is (−); elongation on the prominent cleavage is (−). Rotation angles (corrected A_r) range from $17.2° \pm 0.6°$ at 470 mμ to $24.7° \pm 0.6°$ at 650 mμ. Phase differences (2ϑ) range from $58.0° \pm 6.0°$ at 470 mμ to $-9.0° \pm 1.8°$ at 650 mμ. Microchemical tests show Cu and Te; etch tests are positive for 1:1 HNO_3, 1:1 HCl, $FeCl_3$, and KCN, negative for H_gCl_2 and KOH.

X-ray powder diffraction data show that vulcanite is orthorhombic, with cell dimensions $a = 4.09$ Å, $b = 6.95$ Å, and $c = 3.15$ A. These values are in close agreement with those found for synthetic CuTe by Anderko and Schubert. The probable space group is *Pmnm*.

Twinning and intergrowths in rickardite associated with vulcanite are described briefly. A second telluride, also apparently new, is briefly described pending further investigation.

Introduction

During an investigation of the rotation properties of rickardite in U. S. National Museum Specimen R-933, from the Good Hope Mine, Vulcan, Gunnison County, Colorado, a mineral with even more remarkable optical properties was noted. The same mineral was subsequently found in United States National Museum Specimen 85136, from the same locality. Investigation indicates that it is a compound of copper and tellurium having unit cell constants essentially in agreement with those given by Anderko and Schubert for synthetic CuTe, a compound not heretofore reported as a mineral. The mineral therefore appears to be a new species. We propose to name it vulcanite, after the locality of the Good Hope Mine.

Description of Vulcanite

Both specimens studied consist of fragments of mineralized rock cemented by rickardite, vulcanite, and native tellurium. Intergrown rickardite and vulcanite form a layer 0.5 to 3 mm. thick encrusting each ock fragment. In general, rickardite predominates in the outer part of he layer, next to the rock fragments, whereas vulcanite predominates n the inner part. Tellurium fills the remainder of the spaces between ragments and forms scattered minute grains and small patches in the ickardite-vulcanite crusts as well.

In hand specimen, vulcanite is light bronze to yellow-bronze, with a netallic luster. No crystals are present, hence the morphology cannot be letermined. Cleavage is visible on broken surfaces, but the number and rientation of cleavages are indeterminate. Owing to intergrowth with ckardite, pure material for determining specific gravity is unobtainable. he material is extremely soft (1–2) and somewhat sectile.

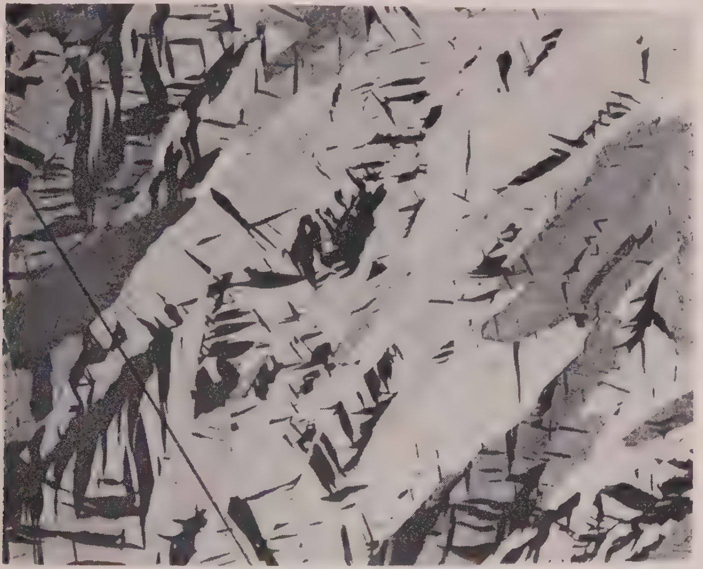

FIG. 1. Elongate irregular laths of vulcanite (pale gray to medium gray) partly replaced rickardite (dark gray). Native tellurium (white) forms three minute northeast-trending ains and an irregular patch at the northeast corner of the photograph. Plain light, ×130

Under the microscope, vulcanite grains range from lath-shaped to arly equant to irregular (Fig. 1). Many grains fall in the range from 1 mm. to 1.1 mm. in length, but where partial replacement by rickard- e is shown (see below) remnants of vulcanite crystals measurable in icrons are abundant. A prismatic or blade-like habit is suggested. Some th-shaped grains have a well-developed lengthwise cleavage, others ow a poorly developed cleavage at right angles to the first, and still hers show only the poorly developed cleavage. We judge that both avages are pinacoidal. Extremely thin twin lamellae along planes nearly but not quite at 45° to the prominent cleavage occur in some grains.

The optical properties of vulcanite are so distinctive that identification of the mineral is a simple matter. They are as follows:

Color: bright yellow or yellow-white to medium blue-gray.

Reflectivity (photoelectric method in white light): maximum, 58.5%, minimum 36.0%. These values are low, possibly by as much as 2–3%, because there are no grains entirely free of scratches, pits, and inclusions of rickardite.

Bireflectance: very strong, as indicated by reflectivity values. Grains showing the well developed cleavage are bright yellow when the cleavage is parallel to the polarizer vibration plane, blue-gray when the cleavage is at the perpendicular position. Elongate grains lacking the prominent cleavage are bright yellow when the long axis is parallel to the polarizer, bluish-gray at the perpendicular position.

Extinction: parallel to cleavage and elongation of laths.

Rotation properties (2):

Rotation sense: (−), relative to the well-developed cleavage and to long axes of plates showing this cleavage.

Anisotropism: very strong; polarization colors (nicols crossed) brilliant yellow-white, grayish yellow-white, yellow-orange, gray, depending on orientation.

Phase difference in white light: (+); the gypsum plate is strongly affected.

Elongation in white light: The principal cleavage direction is length fast. Plates lacking prominent cleavage are length slow.

Polarization figure: DR_r weak, DA_r strong. The field between the isogyres at the 45° position is orange; the areas outside the isogyres are blue.

Rotation angles and values of 2ϑ*:*

	A_r, observed, in degrees	A_r, corrected in degrees	2ϑ in degrees
470 mμ	20.7±.7	17.2±.6	58.0±6.0
520 mμ	24.5±.5	20.4±.4	35.5±3.0
546 mμ	26.2±.5	21.8±.4	26.5±2.5
589 mμ	28.2±.6	23.5±.5	6.1± .8
620 mμ	28.9±.6	24.1±.5	−2.5±1.3
650 mμ	29.6±.7	24.7±.6	−9.0±1.8

In the above, A_r, corrected, is the observed rotation angle corrected for the additional rotation produced by the reflecting plate (2). The value given for 2ϑ is the corrected value. Vulcanite in sodium light gives the highest values of A_r yet recorded for any mineral.

Microchemical: Tests for Cu and Te positive. Etch tests: 1:1 HNO_3 effervesces, staining dark gray; 1:7 HNO_3 effervesces after about 20 seconds, stains brownish gray, and brings out cleavage; HCl bleaches grayish white; $FeCl_3$ instantly darkens, staining light brown; KCN bleaches and then stains light brownish-gray; $HgCl_2$ and KOH negative.

X-ray Data for Synthetic CuTe and Vulcanite

In 1954, Anderko and Schubert (1) reported a study of the system Cu-Te in the region from about 34 to 67 at. % Te. They prepared mixtures in various proportions from electrolytic copper and tellurium of a purity of 99.7%. Samples weighing from 1 to 20 grams were fused in evacuated quartz tubes in a Tamman oven. Maximum weight loss due to volatilizaion of Te in any experiment was 0.4%. Temperatures of fusion ranged upward of 600° C. *X*-ray and microscope studies of the products were supplemented by dilatometer studies. At compositions in the vicinity of 50 at. %, they obtained mixtures of Cu_4Te_3* (synthetic rickardite) and a second phase of entirely different properties. In some preparations, small amounts of native tellurium were also present. From the phases

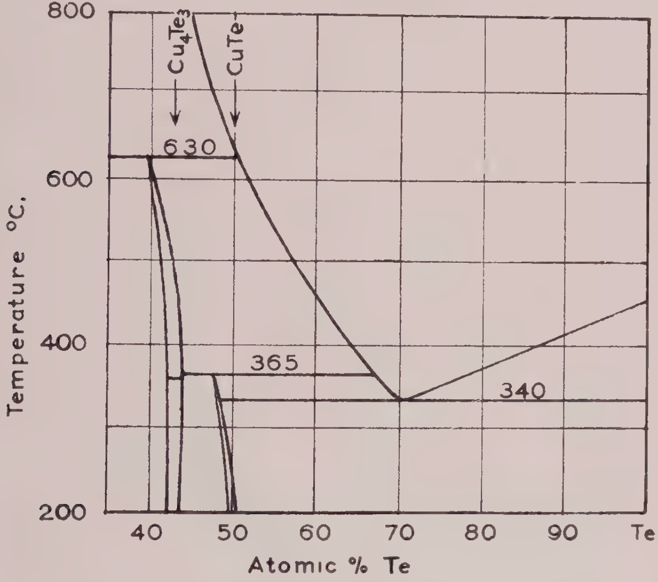

FIG. 2. Tellurium-rich portion of the system copper-tellurium, from Anderko and Schubert.

ound at various temperatures and from *x*-ray studies, they concluded hat the second phase had a composition very close to CuTe. Phase relaions in the tellurium-rich portion of the system Cu-Te as interpreted by Anderko and Schubert are shown in Fig. 2. CuTe appears as a product of peritectic reaction of Cu_4Te_3 with liquid at about 365° and 67 at. % Te.

From *x*-ray powder and single crystal data, Anderko and Schubert oncluded that CuTe is orthorhombic, with $a=3.15\pm0.02$ kX units, $=4.07\pm0.02$ kX units, and $c=6.92\pm0.02$ kX units. They calculated hat the unit cell contains 2 Cu and 2 Te and that the space group is *Pmnm*.

X-RAY INVESTIGATION OF VULCANITE

X-ray powder diffraction data for vulcanite are given in Table I. The alues obtained for interplanar spacings agree with values calculated from values of $\sin^2\theta$ for CuTe given by Anderko and Schubert. The pattern is indexed on the basis of an orthorhombic unit cell with $a=4.09$ Å, $b=6.95$ Å, and $c=3.15$ Å. These values are in close agreement with those of Anderko and Schubert, except that we have transposed the axes to agree with the conventional form $b>a>c$. If the axes as reported by Anderko and Schubert for CuTe are similarly transposed, the space group for CuTe becomes *Pmnm.*

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* According to Forman and Peacock (4), the formula of rickardite is $Cu_{4-x}Te_2$.

Several fragments of vulcanite were removed from our specimens for single crystal photographs, but all photographs taken are too indistinct to be usable, apparently because the fragments were deformed during removal. Extreme care in removal of fragments from the polished surfaces failed to resolve the difficulty.

TABLE I. *X*-RAY POWDER DATA FOR VULCANITE (CuTe)

Pmnm; $a_0=4.09$ Å, $b_0=6.95$ Å, $c_0=3.15$ Å

Cu/Ni radiation, $K_\alpha=1.5418$ Å; Camera diameter 114.6 mm.

I (Est.)	*d*(Obs.)‡	*d*(Calc.)	*hkl*
4	6.94	6.95	010
0.2	3.88*		
6	3.52	3.52	110
3	3.47	3.48	020
0.2	3.34†		
0.2	3.23*		
0.2	3.18	3.25	?(001)
7	2.86	2.87	011
3	2.65	2.65	120
1.5	2.49	2.50	101
3	2.35*	2.34 2.35	021 111
3	2.32	2.32	030
0.5	2.24*		
2	2.05†	2.05	200
10	2.03	2.03 2.02	121 130
1.5	1.866	1.866	031
2.5	1.762	1.762	220
0	1.738	1.738	040
0.2	1.701	1.698	131
2	1.665	1.665	211
0.2	1.597	1.599	140
1.5	1.576	1.575	002
1	1.532	1.533 1.536	230 012
2	1.521	1.522	041
1.5	1.439	1.438 1.435	112 022
1	1.425	1.426	141
1	1.391	1.390	050
0.5	1.376	1.378	231
0.5	1.353	1.354	122
0.5	1.337	1.338	310
1	1.324	1.324	240
0.5	1.301	1.302	032
2	1.271	1.272 1.269	051 320
0.5	1.249	1.251 1.248	301 202
2	1.241	1.241	132
2	1.225 1.214	1.228 1.214	212 151
2.5	1.177	1.175	330 222
0.2	1.158	n.d.	
0.2	1.150	n.d.	
2	1.115	n.d.	
0.5	1.100	n.d.	
1	1.081	n.d.	

* Lines due entirely or in part to native tellurium.

† Lines due entirely or in part to rickardite.

‡ Corrected for film shrinkage.

In our powder photographs, there are a number of weak lines that cannot be indexed. These are probably due to impurities of rickardite and native tellurium. One line at 3.18, not accounted for by these contaminants, is near the calculated value of the (001) reflection of vulcanite. However, if the space group of vulcanite is *Pmnm*, indicated by Anderko and Schubert for synthetic CuTe, this reflection is prohibited. It is quite possibly due to some unidentified impurity, particularly since the difference between observed and calculated values is 0.03. Except for the line at 3.18, the indices for other lines are consistent with space group *Pmnm;* however, there are insufficient reflections of the type ($h0l$) to prove conclusively that vulcanite belongs to this space group.

So far as the optical and physical properties of CuTe are given by Anderko and Schubert, they agree with those observed for vulcanite.

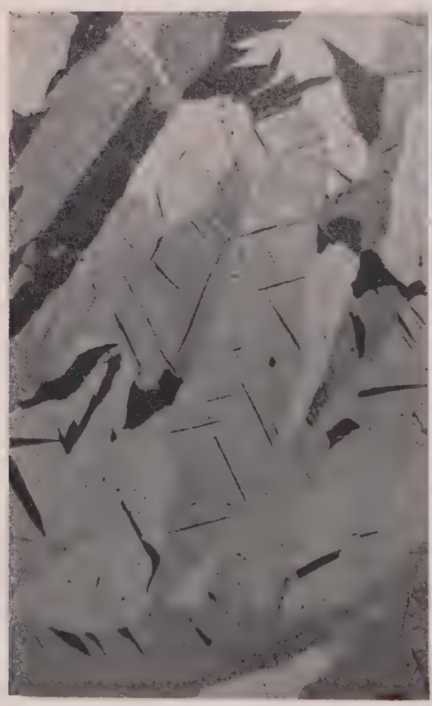
TEXTURAL FEATURES OF VULCANITE AND ITS RELATIONS TO RICKARDITE AND TELLURIUM

The outstanding textural features of the specimens studied are the variety and complexity of intergrowths of vulcanite and rickardite and the relationships of these two minerals to native tellurium. The simplest intergrowths are of the type shown in the central part of Fig. 3, in which thin blades of rickardite occur in two sets oriented at a high angle to one another and roughly at 45° to the length of the vulcanite host grain. Vulcanite grains showing the prominent cleavage may show two sets of nclusions, like the grain figured, and a third set parallel to the cleavage. These intergrowths are of the kind commonly produced by exsolution. Anderko and Schubert found identical intergrowths in synthetic CuTe and concluded that with cooling, excess Cu in CuTe was exsolved as rickardite. The similarity of intergrowths in the synthetic and natural materials is so remarkable that one would infer that vulcanite, as initially deposited, was likewise a solid solution.

In the natural material, however, a variety of intergrowths due to partial replacement of vulcanite by rickardite is present. In the rickardte-vulcanite crusts, vulcanite is most abundant in a zone bordering native tellurium. In this zone, only incipient replacement by rickardite s shown. Away from the native tellurium, the grains of vulcanite show progressive replacement by rickardite, and adjacent to the rock fragments there is a zone in which only remnants of vulcanite are present. Replacement is guided by the same sets of planes in vulcanite as those along which rickardite inclusions occur in Fig. 3. The relationships are shown in Fig. 4. In the central part of the figure irregular laths of vulcanite extend nearly across the full length of the photograph. At the bottom, where vulcanite borders a body of native tellurium, replacement of vulcanite by rickardite has not progressed far, but in the upper part of the photograph replacement is nearly complete, and only remnants of the laths remain. In the incipient stage, however, oriented inclusions of rickardite in vulcanite are produced. Every gradation between intergrowths of the type of Fig. 3 and those of Fig. 4 is shown in polished sections. The replacement intergrowths are also illustrated in Fig. 1.

In view of the complexity of relationships, the origin of individual intergrowths is not always clear. We judge, however, that intergrowths such as those of Fig. 3 are due to exsolution of rickardite from vulcanite.

Textural relationships of native tellurium to the other minerals are likewise varied. Boundaries of tellurium with vulcanite and rickardite are in general complex and interpenetrating. Tellurium has formed by replacement of the other two minerals, along grain boundaries, along



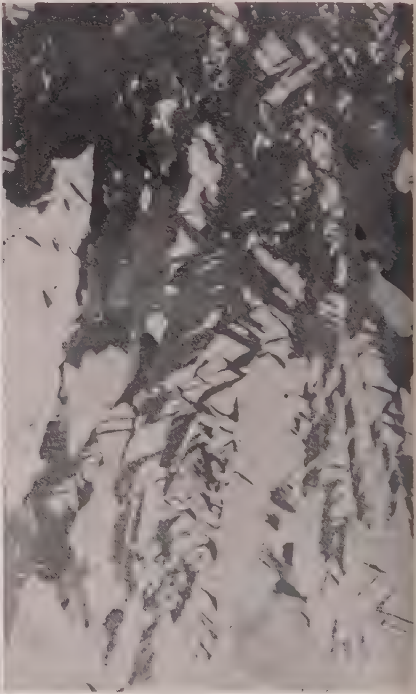


Fig. 3 (left). Vulcanite (pale to medium gray) and rickardite (dark gray), with a patch of native tellurium (white, bottom margin). The oriented intergrowth in the vulcanite grain in the central part of the field, and similar intergrowths elsewhere in the field, have the characteristics of exsolution intergrowths. The coarser intergrowths at the top and lower left are of the type produced by partial replacement of vulcanite by rickardite, as illustrated in Fig. 4. Plain light, ×190.

Fig. 4 (right). Progressive replacement of irregular laths of vulcanite (pale gray to medium gray) by rickardite (darker shades of gray), guided by crystallographic directions of vulcanite. At the bottom, rickardite occurs as thin discs and incipient networks in vulcanite. At the top, only remnants of vulcanite in rickardite are present. Plain light, ×70.

cleavages and other crystallographic planes, and locally along fractures. Despite the gross crustification shown by the ore specimens, the three minerals have clearly not formed by simple cavity filling.

The paragenetic sequence indicated is therefore vulcanite (earliest), rickardite, and tellurium (latest). This means a change, in successive phases deposited, from Cu:Te=1:1 to Cu:Te ca 4:3, and then to Cu:Te=0. This is a puzzling sequence—a simple sequence tellurium-vulcanite-rickardite, involving a progressive increase in Cu:Te ratio, or a sequence rickardite-vulcanite-tellurium, involving a decrease in Cu:Te ratio, would be easier to understand. The experiments of Anderko and Schubert are of interest here. They found that in alloys with composiions in the neighborhood of 50 at. % Te, the phases present and their abric depend on the conditions of cooling. A melt of 50 at. % Te at 300° C., when quenched in water (their Fig. 3) gave a mixture of Cu_4Te_3, CuTe with exsolution discs of Cu_4Te_3, and a eutectic of CuTe and Te. This is a disequilibrium assemblage, for the stable phases at this composition (Fig. 2) should be Cu_4Te_3 and CuTe. The ore here described would appear likewise to be a disequilibrium assemblage, but in all probability was formed in an open system rather than a closed one.

As an alternative, it may be that in the ore body as a whole vulcanite was replaced by rickardite, in open system, and that the excess tellurium was taken into solution but later deposited at certain points in the ore ody, partly by replacement of both the earlier minerals. Without knowldge of mineral relations throughout the ore bodies of the Good Hope Mine, including the three-dimensional mineral distribution and proporons therein, the interpretation is purely speculative. However, from he work of others on ores of the Good Hope Mine, it seems evident that he ores varied in mineral composition from place to place, and that vulnite was not everywhere present. So distinctive a mineral could have arcely have been overlooked.

In the synthetic system (Fig. 2), CuTe is deposited at a temperature etween 340° C. and 365° C. The direct applicability of the phase diaram to natural systems, however, is open to the usual questions.

Watanabe's Work on Weissite

So far as we can determine, CuTe has not previously been recognized a mineral. However, in 1938 (5), and again in 1950 (6), Ramdohr rerred to a work in Japanese by M. Watanabe, in which both natural and nthetic copper tellurides were apparently discussed. Ramdohr stated at according to Watanabe's findings, weissite corresponds to artifilly prepared Cu_2Te, which can hold about 5% Te in excess and then rees fully with analyzed natural weissite. Watanabe described weise, however, as cream-white to dark blue, whereas Ramdohr and other investigators (7, p. 113; 8, p. 357) describe weissite as light gray, similar to chalcocite, weakly bireflectant, and moderately anisotropic in pink, bluish gray, and blue. Weissite as thus described has been definitely established as a mineral species (8), but it is clearly not vulcanite. Yet from Watanabe's description of bireflectance as quoted by Ramdohr, it is conceivable that the substance described by Watanabe as weissite may actually have been that described here as vulcanite. Unfortunately, Watanabe's work is not available to us.

NOTES ON RICKARDITE

Rickardite in the specimens studied exhibits a complex pattern of polysynthetic twinning along two sets of planes that are probably at right angles to one another (Fig. 5). This type of twinning is strongly suggestive of inversion from a high-temperature form to a low-temperature form. In 1907, from a study of the system CuTe, Chikashige (3) recognized an inversion at or near 365°, and this temperature has been confirmed by Wassermann, Wallbaum, and Keymling (private communication to Anderko and Schubert) and by Anderko and Schubert (1). The latter authors (their Fig. 1) show twinning in synthetic Cu_4Te_3 that appears identical with that of our Fig. 5. Ramdohr (6) noted inversion

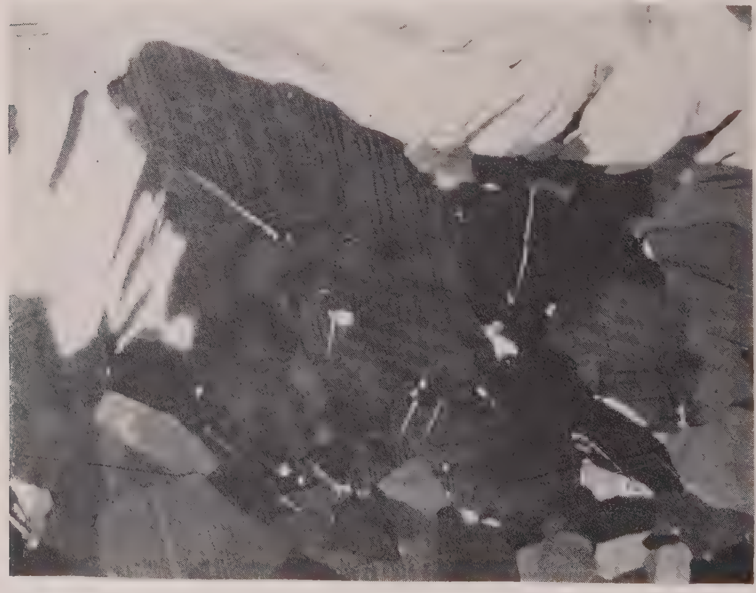


FIG. 5. Rickardite (medium to dark gray), showing complex twinning. In the large crystal in the upper half of the field a thin blade of vulcanite (white) is oriented at about 45° to the twinning, but other blades show variation in orientation. White to light gray grains are vulcanite. Crossed nicols, ×140.

twinning in rickardite from the Good Hope Mine and suggested that the high temperature form might be cubic. Anderko and Schubert obtained a diffraction pattern from the high-temperature form, but the vagueness of the lines at high reflection angles prevented definite indexing. They state that a cubic indexing appeared excluded, but a relationship to the structure of CuS appeared to be shown.

The orthogonal pattern of twinning shown by rickardite in the material studied here suggests that the high-temperature form has either a cubic symmetry as suggested by Ramdohr, or a higher order of tetragonal symmetry, but further investigation of this matter is necessary.

Just as vulcanite contains inclusions of rickardite, rickardite in many places contains oriented inclusions of vulcanite that appear to be of the same origin and suggest that rickardite, as first deposited, contained excess Te. The inclusions are commonly oriented at about 45° to the complex twinning, more rarely parallel to it, but there is some variation in orientation.

UNKNOWN MINERAL

An unknown mineral occurs in the polished sections studied as patches of anhedral grains with the following properties:

Color: medium brownish-gray (liverwurst gray).
Reflectivity: 32% in white light, by photoelectric method.
Bireflectance: weak but perceptible, more grayish to more brownish as the stage is rotated.
Specific gravity: not determinable from material at hand.
Hardness: not greater than 2.
Cleavage and twinning: none observed.
Polishing characteristics: polishes smoothly. Polishing hardness < vulcanite and rickardite.
Anisotropism: distinct; polarization colors (nicols exactly crossed) medium gray, slate-gray, gray with brownish tint. With analyzer slightly uncrossed, a golden-brown color is seen.
Polarization figure: at 45° position isogyres are black, with an orange tint on concave sides. Center of field is bluish gray.
Sign of phase difference in white light: (−), effect on gypsum plate is distinct.
Rotation angles and 2ϑ:

Wavelength	Observed A_r in degrees	Corrected A_r in degrees	2ϑ in degrees
470 mμ	$2.2 \pm .1$	$1.8 \pm .1$	$-1.7 \pm .1$
520 mμ	$1.5 \pm .1$	$1.2 \pm .1$	$-2.7 \pm .1$
546 mμ	$1.3 \pm .1$	$1.0 \pm .1$	$-2.2 \pm .1$
589 mμ	$0.8 \pm .1$	$0.6 \pm .1$	$-2.4 \pm .1$
620 mμ	$0.4 \pm .1$	$0.3 \pm .1$	$+2.9 \pm .1$
650 mμ	$0.0 \pm .2$	$0.0 \pm .2$	$+3.1 \pm .1$
589 mμ (oil *n* 1.515)	$0.9 \pm .1$	$0.7 \pm .2$	$-3.7 \pm .1$

The corrected values are the observed values corrected for the effect of the reflecting plate. Values for 2ϑ are corrected values. It will be noted that the mineral is essentially isotropic at 650 mμ and that the sign of 2ϑ passes through zero between 589 mμ and 620 mμ.

Qualitative microchemical tests indicate that the mineral contains Cu and Te, but material sufficient for quantitative chemical analysis or for spectrographic analysis with equipment available to us cannot be obtained from the specimens.

The X-ray powder pattern of the mineral cannot be identified with that of any known mineral species. Incomplete single crystal studies indicate that the mineral is hexagonal. Further studies are in progress and additional material is being sought with the aim of characterizing the mineral properly.

ACKNOWLEDGMENTS

We are greatly indebted to Dr. George K. Switzer, Curator of Mineralogy, United States National Museum, for the loan of the specimens here discussed. Dr. S. W. Bailey, of our Department, has been a generous advisor in the x-ray work. The investigation here described has been supported by a grant from the Wisconsin Alumni Research Foundation, for which we wish to express our appreciation. Mr. Ian Threadgold is indebted to the Commonwealth Scientific and Industrial Research Organization of Australia for approval of publication.

REFERENCES

1. ANDERKO, K., AND SCHUBERT, K. "Untersuchungen im System Kupfer-Tellur," *Zeit. für Metallkunde*, **4,** Heft 6, 371–378, 1954.
2. CAMERON, E. N., "Apparatus and techniques for the measurement of certain optical properties of ore minerals in reflected light," *Economic Geology*, **52,** 252–268, 1957.
3. CHIKASHIGE, M., "Über Kupfer-Tellur," *Zeit. für anorg. allgemeine Chemie*, **54,** 50–57, 1907.
4. FORMAN, S. A., AND PEACOCK, M. A., "The crystal structure of rickardite, $Cu_{4-x}Te_2$," *Am. Mineral.*, **34,** 441–451, 1949.
5. RAMDOHR, P., "Erzmikroskopische Untersuchungen an einigen seltenen oder bisher wenig beachteten Erzmineralien, *Centralblatt fur Mineralogie*, **1938, A,** 129–136.
6. RAMDOHR, P., "Die Erzmineralien und ihre Verwachsungen," Akademie Verlag, Berlin, 827, p. 1950.
7. SHORT, M. N., "Microscopic determination of the ore minerals," *U. S. Geol. Survey, Bull.* **914,** 314 p., 1940.
8. THOMPSON, R. M., "The telluride minerals and their occurrence in Canada," *Am. Mineral.*, **34,** 342–382, 1949.

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Note: On the eve of transmittal of the manuscript of this paper, the authors received a communication from Dr. Paul Ramdohr, saying that he has been studying a mineral, in an ore from a Japanese locality, which he concludes is also CuTe. This indicates a second occurrence of vulcanite. Like the authors, Dr. Ramdohr infers that the pleochroism reported by M. Watanabe for weissite was that of natural CuTe.

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DIELECTRIC BEHAVIOR OF ROCKS AND MINERALS*

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ABSTRACT

A reconnaissance study of the dielectric constants of twenty-three common mineral and seventy-one rock samples was made at thirteen frequencies in the range 50 cps to 00 megacycles. Dispersion was observed for all rock samples tested and for a few minerals at the lower end of the frequency spectrum. Moisture in a rock can increase the dielectric constant by an amount greater than is predicted by simple mixing rules. Water appears o be the principal constituent of the rock controlling the dispersion. The observed dispersion was similar in form to Maxwell-Wagner type polarization, but was quantitatively much greater. Some form of electrode or membrane polarization appears to be the most kely explanation. The dispersion is probably a result of the same mineral properties on which induced-polarization methods of geophysical prospecting are based.

INTRODUCTION

The electrical behavior of matter is controlled basically by three physical properties: electrical conductivity, magnetic permeability and dielectric constant. Values of the electrical conductivity and magnetic permeability of mineral materials and the factors controlling their variations are relatively well known. On the other hand, the dielectric behavior f matter is less studied and more poorly understood than almost any ther physical property. This paper reports a reconnaissance study of the dielectric behavior of a few common earth materials, and it attempts to explain their behavior in terms of fundamental physical processes.

Dielectric "constant" is not a constant at all in the usual physical meaning of the word. It is a property which depends on such variables as emperature, pressure and frequency of alternating voltage. Fundamentally, it is the ratio of the average electrical charge displacement per unit area in a body to the electrical stress displacing it. Mathematically his is expressed

$$\overline{D} = KK_v\overline{E} \qquad (1)$$

here $\overline{D}$ is the vector electric displacement, $\overline{E}$ is the vector electric field, is the relative dielectric constant and K_v the permittivity of a vacuum.

It is more common to find dielectric constant defined in terms of a arallel-plate capacitor. According to this definition, the dielectric con- ant of a material is the ratio of the capacitance, C, of the capacitor with the material between the plates to the capacitance, C_0, of a similar capacitor in vacuo

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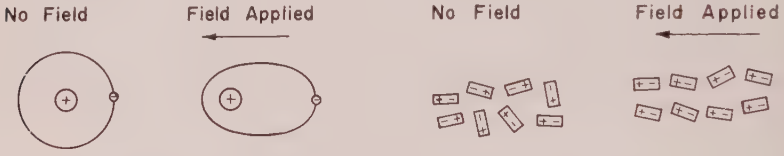
* Contribution No. 59-37, College of Mineral Industries, The Pennsylvania State Uni- rsity.

† This article is a condensation of a Ph.D. thesis by the junior author. The complete esis is on file in The Pennsylvania State University Library.

$$K = \frac{C}{C_0} = \frac{q/V}{q_0/V_0} \tag{2}$$

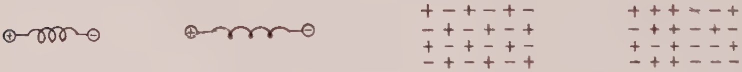
where the charge on the plates and the voltage between them are q and V with the material present, and q_0 and V_0 in vacuo.

The amount of charge which will exist on a pair of plates held at a given potential with respect to each other depends on the nature of the material between the plates. The dielectric constant of a material is equal to the ratio of the charge which will be present with the material between the plates to the charge which will be present in vacuo. Thus, the larger the dielectric constant of the material, the larger the charge which will be present.



a. Electronic Polarization

c. Dipole Polarization



b. Atomic Polarization

d. Interfacial Polarization

FIG. 1. Different types of polarization (after Von Hippel 1954A).

The charge on the capacitor plates is present because of polarization which occurs within the dielectric material. There are a number of different ways in which this polarization can occur. In all cases the polarization is a result of the relative displacement of positive and negative charges within the material. The different types of polarization generally take different lengths of time to form, which is equivalent to saying that each can be observed only below a characteristic frequency of alternating voltage. Electronic polarization (Fig. 1) results from displacements of the electron clouds surrounding an atomic nucleus. Such displacements can occur at frequencies in the visible and ultra-violet spectrum. Resonances of the electrons involved in displacements of this sort contribute to the absorption spectrum of a material.

Another cause of polarization is the motion of atoms in a crystal lattice. In an electrical field the positively and negatively charged atoms are displaced from their normal positions in very small amounts. Such displacements become important at lower frequencies than for electronic polarization. Resonances occur typically in or near the infra-red spectrum.

A third type of polarization becomes important at radio frequencies. Debye (1912) postulated that the molecules of substances in which charges are not symmetrically arranged possess an electric moment which is characteristic of the molecule. When an electric field is applied, these molecules tend to align themselves with their dipole axes in the direction of the field. This is called dipole polarization. It can result also from alignment of domains or defects in a solid.

The three types of polarization considered so far are to be expected in homogeneous materials. In heterogeneous materials there is an additional type of polarization which can occur. In many materials some of the charges are relatively free to move about within the material. The degree of freedom depends on the material. In copper and aluminum some electrons are particularly free, resulting in high conductivity for these materials. In electrolytes both positive and negative ions are free to move. Even in relatively good insulators a few charges may be free to travel limited distances. If two materials adjoin in which the freedom of the charges to move differs, charges will accumulate along the interface in the presence of an electrical field. This phenomenon is called interfacial polarization. Interfacial polarization generally takes longer to form than the other types discussed. Therefore, it is rarely important above radio frequencies. Because of the effects of interfacial polarization, it is obvious that the dielectric constant of a mixture of materials may exceed that of either material alone.

As a result of these different mechanisms, dielectric constant will generally be greater at low frequencies than at high frequencies. Each of the different types of polarization adds to the dielectric constant. This is shown schematically in Fig. 2. In the case of electronic and atomic polarization, resonances are commonly sharp, so that there may be peaks and troughs in the curve. Sharp fluctuations are less common for dipole and interfacial polarizations. Ideally, the polarization takes effect asymptotically centered on a frequency known as the relaxation frequency. Figure 2 is drawn diagramatically to bring out the separate effects. Actually the several steps of dielectric-constant increase may merge. For a heterogeneous material like a rock, it would be expected that there might be as many forms of interfacial polarization as there are varieties of interface between the various grains and contained fluids.

EXPERIMENTAL PROCEDURES

Dielectric constant was determined by measuring the capacitance of a parallel-plate capacitor with a round disc of the material being tested between the plates. To obtain these discs, plugs were cut from rock and mineral specimens using a diamond core drill. A range of sizes from $\frac{7}{8}''$ to 2″ diameter was obtained, depending on the size of the original specimen. Discs from 50 to 150 mils thick were sliced from the cylindrical cores using a diamond saw. The discs were ground and polished to obtain as nearly as possible smooth, parallel faces. Because of porosity, the rock surfaces generally retained some roughness.

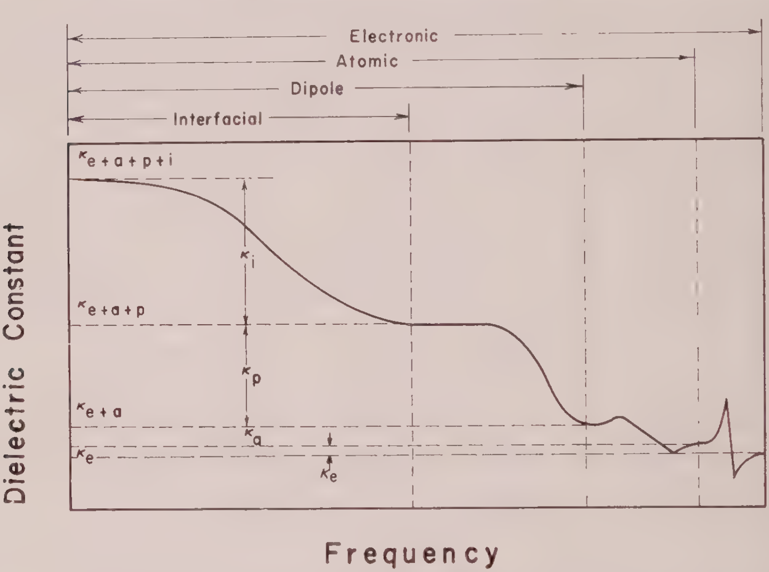


FIG. 2. Idealized graph showing the variation of dielectric constant with frequency as a result of different types of polarization.

Since failure to make intimate contact between the sample and the plates of the capacitor may result in a series air capacitance, metallic electrodes were affixed directly to the sample. One type consisted of 50-50 per cent tin-lead foil coated with petrolatum and pressed onto the sample face with a rubber roller. Under vacuum the foil sometimes loosened and separated from the sample, so that for most measurements it was replaced by a coating of conductive silver paint brushed onto the sample surface.

It is obvious from the discussion presented above that it is desirable to measure dielectric constant over as wide a range of frequencies as posssible. Comparison of the measurements reported below with those of other investigators was of doubtful meaning in many cases because the frequency at which the other measurements were made was not reported. In the research described below capacitance was measured at a sequence of thirteen frequencies between 50 cycles per second and 30 megacycles. At least two measurements were made per decade. It was felt that this would permit the observation of any dispersion phenomena inasmuch as such phenomena are usually observable over several decades. Below 300 kilocycles a General-Radio Model 716-C capacitance bridge was used, with a Hewlett-Packard Model 200-C audio oscillator for a signal source and a General-Radio Model 736-A wave analyzer for a null detector. The bridge signal was monitored with a cathode ray oscilloscope. Above 400 kc. a General-Radio Model 821 Twin-T bridge with a General Radio Model 1330-A oscillator and a Collins Model 51J-3 communications receiver for a null-detector was used. The bridges were balanced both for capacitance and resistive loss. As the bridges are intended for use with low-loss capacitors only, their accuracy becomes poor for capacitors having appreciable conductance. Therefore, the dielectric constants of the more highly conductive minerals such as most sulfides and fully water-saturated sedimentary rocks can not be determined by this apparatus.

An important aspect of dielectric measurements is the means of holding the sample during the measurement. One of the main requirements placed upon a sample holder is that the configuration of the electrodes be such that the distribution of the field is known. Initial measurements were carried out using a General Radio Model 1690-A sample holder. This unit, utilizing circular-plate electrodes, is a refined model of the sample holder described by Hartshorn and Ward (1936). The electrode surfaces are precision-ground and a precision micrometer screw is used to drive the movable electrode with respect to the fixed electrode.

Early measurements on rock samples which had been oven-dried prior to measurement indicated that the samples were possibly adsorbing minute amounts of moisture from the atmosphere, which led to considerable variation in their dielectric constants during the course of measurement. To remedy this, an air-tight container was placed around the sample holder and a desiccant (P_2O_5) was put inside. Although this appeared to reduce the variability, some drift of dielectric constant was still noted. This led to the construction of an evacuable sample holder consisting of a brass plate contacting the bottom of the sample and a conical point electrode on a micrometer adjustment contacting the conductive-paint film on the top of the sample (Fig. 3).

In the case of dry samples, after cutting and applying electrodes to the sample faces, the sample was placed in a 100° C. drying oven for a minimum of 24 hours. The sample was then removed from the drying oven and immediately placed in the sample holder. Evacuation was initiated and maintained at several millimeters of mercury for at least an hour prior to measurement. Evacuation was continued during the course of measurement. This same holder without evacuation was frequently used when measurements were made under room or natural conditions.

Where samples containing moisture were measured, partial saturations were obtained using evaporation techniques described by Holmes (1954, 1958). Since several per cent weight loss normally occurred during the time of measurement, the water saturation was taken as the average of the saturations determined by weighing immediately prior to and after measurement.

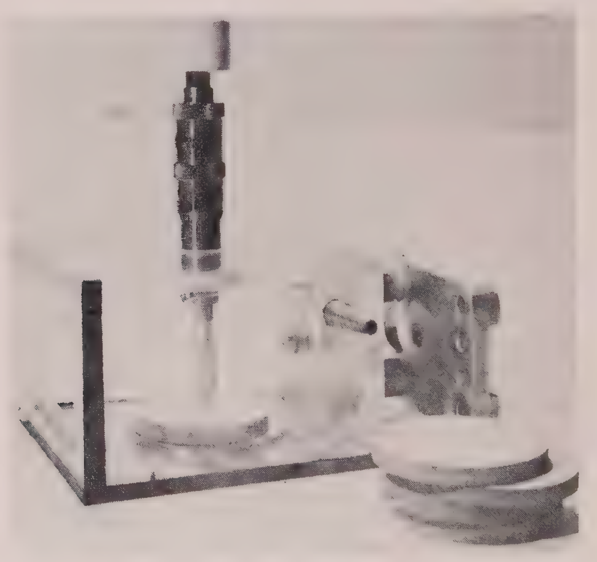


FIG. 3. Evacuable cell for dielectric-constant measurements.

For measurements at elevated temperatures, the sample holder consisted of an oven (Temco Model GRP) with two stiff bare copper wires with silver tips. The sample was placed between these wires, one of which was pivoted. Temperature was measured through use of a thermocouple placed in close proximity to the sample.

Except where otherwise stated, all measurements were made at room temperature which ranged between 22° C. and 34° C.

The precision capacitors in both capacitance bridges used in this research are claimed by their manufacturer to provide direct readings correct to ±0.2 *μμf*. When corrections supplied with the bridges are used, in conjunction with measuring differences in capacitance rather than a single direct reading, an accuracy of ±0.1 *μμf* is claimed. Since the lowest value of a sample capacitance read was 5 *μμf*, this represents maximum inaccuracy of 2 per cent under most circumstances. The instrument can be read to a precision of about 0.05 *μμf*.

In measuring values of capacitance which fell beyond the limits of the standard bridge-balancing capacitors (1000 *μμf*), as was the case for the rocks containing bulk moisture, external variable capacitors (CDB-5, CDC-5) were required. The tolerance of these as specified by the manufacturer was ±5 per cent.

It was possible to repeat null positions to within one half of a scale division, each division being 0.1 *μμf*. A check on the over-all instrumentation was made by measuring a sample (of Kralastic EBMU) which had been previously measured at the General Radio Company and checked against their calibration standards. Their value for its dielectric constant was 4.46 as compared to a value of 4.48 obtained here.

To check the reproducibility of the measurements made on individual samples, the general practice of repeating the 50 *cps* measurement after each run was established. For the minerals and dry rocks, a maximum dielectric-constant variation of eight per cent was found between the two readings. In a majority of cases this variation was less than two per cent. Most or all of this variation could be due to changes occurring within the sample during measurement, such as loss or adsorption of small amounts of moisture.

For the samples containing free moisture, it was not possible to obtain such data on reproducibility, since several per cent weight loss often occurred during the course of the measurements.

To determine the combined reproducibility of both the measuring technique and sample treatment, measurements were made on three immediately adjacent samples of the Bartlesville sandstone. Each sample was exposed to the same treatment in its preparation for measurement and was measured under the same vacuum conditions. The resulting data, treated statistically, gave the most probably error of dielectric constant as .068 (out of 4.6 to 5.3) between measurements made at any given frequency. This "error" included that due to any compositional or structural variations between samples.

DIELECTRIC CONSTANTS OF MINERALS

The dielectric constants of twenty-three samples of nineteen common minerals were measured. The data are summarized in Table I and Figs.

TABLE I. DIELECTRIC CONSTANT OF MINERALS EXHIBITING LITTLE OR NO DISPERSION

Sample	Source	Cut	Dielectric Constant 100 cps.	Dielectric Constant 10 mc.
Quartz	Brazil	perp. *c*-axis	4.59	4.51
Quartz	Brazil	parallel *c*-axis	4.60	4.50
Quartz	Brazil	45° *c*-axis	4.69	4.61
Biotite	Pontiac Co., Que.	para. bas. cleav.	4.86	4.78
Phlogopite	Denboln Twp., Que.	para. bas. cleav.	6.21	6.10
Lepidomelane	Faraday Twp., Ont.	para. bas. cleav.	4.06	3.93
Muscovite	Mattawan Twp., Ont.	para. bas. cleav.	6.74	6.60
Calcite	Unknown	perp. *c*-axis	7.60	7.60
Calcite	Unknown	parallel *c*-axis	7.30	7.30
Halite	Harshaw Chem. Co.	para. cleav.	5.85	5.85
Gypsum	Wayne Co., Utah	perp. *b*-axis	4.24	4.23

4, 5 and 6. The minerals studied were chosen on the basis of availability of samples of the most common types. Many minerals which might appear appropriate for this study are omitted because samples of sufficient purity, size or form were not available when the measurements were being made. The values of 4.5 to 4.7 obtained for quartz lie in the range

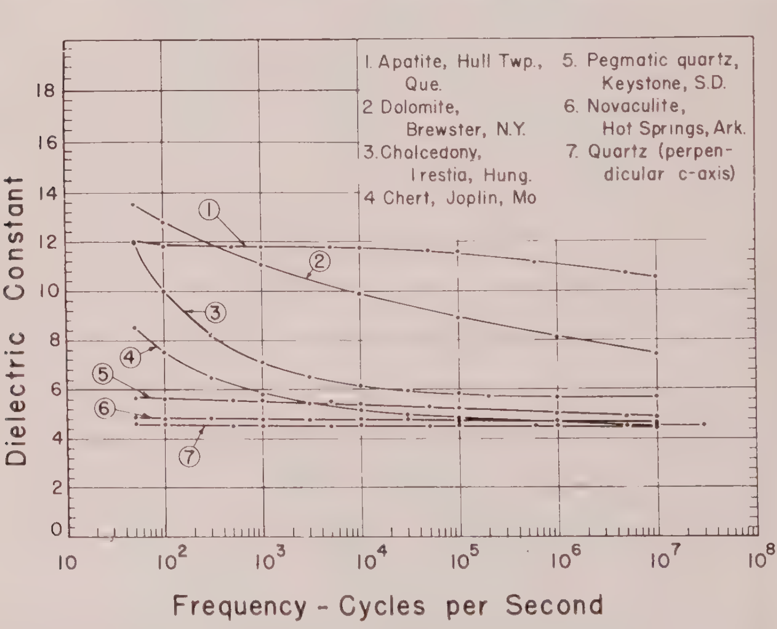


FIG. 4. Measured values of relative dielectric constant for apatite, dolomite and quartz.

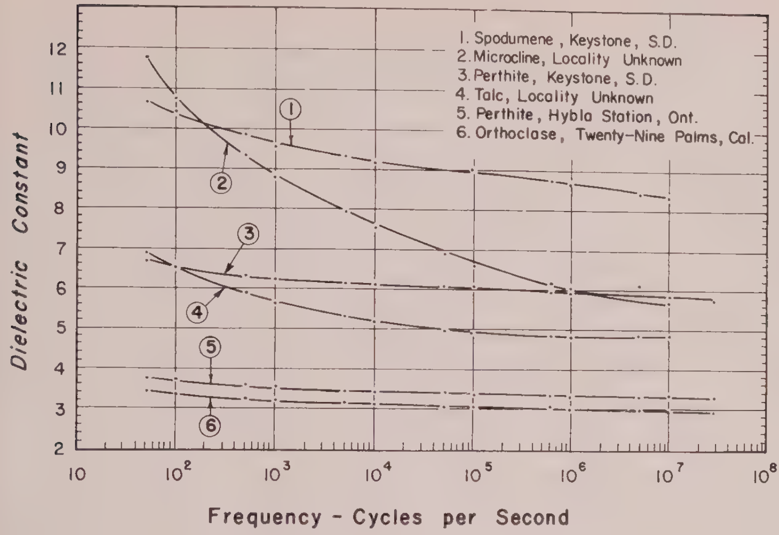


FIG. 5. Measured values of relative dielectric constant of some silicates.

of other published figures (e.g. Cady, 1946; Rao, 1947; Smithsonian Physical Tables, 1933). Novaculite, pegmatitic quartz, chert and chalecedony had dispersed, higher values of dielectric constant.

The four samples of mica tested had invariant values of dielectric constant to the accuracy of the measurements. The observed values are in the same range or lower than the values of 5.4–11.5 reported by Von Hippel (1945B) and Slichter and Telkes (1942). The dielectric constants

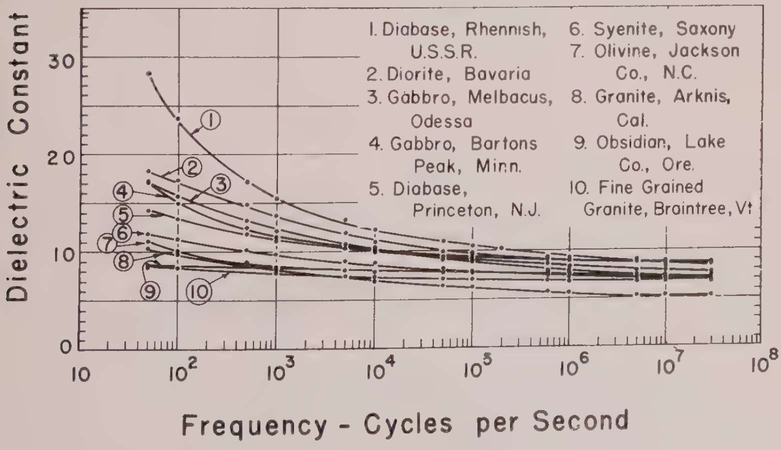


FIG. 6. Measured values of relative dielectric constant of some igneous rocks.

of the other silicates tested were all dispersed (Fig. 5). The single-crystal orthoclase showed the least and the polycrystalline bytownite the most dispersion. The values observed spanned the range of 5.45 to 7.22 reported by Takubo and associates (1953) for powdered samples of plagioclase feldspars.

The values of 7.6 and 7.3 obtained for calcite were constant, but lower than those reported by others. Rao (1949) and the Smithsonian Tables (1933) give values of 8.7 (at 1.6 mc.) and 8.49 (d.c.) for the perpendicular cut and 8.2 and 7.56 for the parallel cut. Halite and gypsum also lacked dispersion, but dolomite showed a variation. Takubo *et al.* (1953) report a value of 5.55 for the dielectric constant of halite at 1.6 mc., and 5.02 and 4.98 for two samples of gypsum at 100 mc. Slichter and Telkes (1942) and Rao (1949) quote figures of 6.3 for gypsum, 5.6 to 6.36 for rock salt (no frequency stated) and 6.8 and 7.8 perpendicular and parallel to the axis for dolomite (at 400 mc.).

Apatite had one of the most unusual dielectric constants measured (Fig. 4). Its curve was nearly flat at low frequencies and fell off at high frequencies. Slichter and Telkes (1942) quote lower but not inconsistent values of 9.5 perpendicular to the axis and 7.4 parallel to the axis at a frequency of 400 mc., which is higher than the frequency range covered here. Rao (1949) quotes figures ranging from 7.4 to 10.5 at 1.6 megacycles.

The small differences between the values reported here and those of other investigators could represent variations within the range of possible values for these minerals as a result of the presence of impurities or allowable types of structural variation; they could be the result of the different methods of measurement including the differences in the frequencies at which the measurements were made; or, less likely, they could be the effects of differences in the temperatures at which the different measurements were made.

DIELECTRIC CONSTANTS OF ROCKS

Dispersion was observed in the case of all rock samples tested. Figure 6 shows the dielectric constant of ten igneous rocks, and Fig. 7, the dielectric constant of six metamorphic rocks. The values observed at high frequencies are comparable to those reported by others (Slichter and Telkes, 1942; Rao, 1948). Marble showed the least dispersion, from 9.20 at 100 cps at 8.90 at 10 mc.

In the case of sedimentary rocks, the dielectric constant depended greatly on the moisture content. Figures for the dielectric constant of dried and natural-state Morrison sandstone samples have already been published by Keller and Licastro (1959). Similar results were obtained

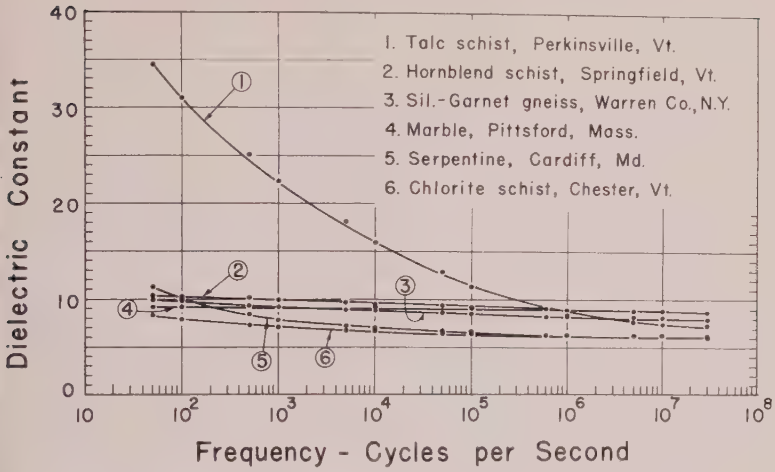


Fig. 7. Measured values of relative dielectric constant of some metamorphic rocks.

for samples of Bradford sandstone, Wilcox sandstone and Bartlesville sandstone. Even after drying under vacuum a small dependence of dielectric constant on frequency was generally observed. Values increased from 4.0–4.9 at 10 megacycles to 4.5–5.4 at 50 cps. (Compare these values with the dielectric constant of quartz of 4.5–4.7. The lower values for sandstone are expectable as a result of porosity.) Natural-state and artificially saturated samples all exhibit dispersion. Figure 8 compares he dielectric constant of a typical sample of Wilcox sandstone under natural-state (atmospheric) conditions with the same sample under vacuum and subsequent saturation with distilled water.

The dielectric constants of five typical samples of carbonate sediments are shown in Fig. 9. Values of calcite and marble are included for comparison.

Factors Influencing Dielectric Constant

The factors influencing dielectric constant can be divided into three groups. First, the chemical composition of the material has an effect as shown by comparing the range of compositions among the feldspars and micas. Second, the crystal structure can be expected to influence the dielectric constant, though this is not obvious from the data reported here, as no pairs of samples of the same chemical composition and different crystal structure are included in the list. Third, the relations of the various constituents of the rocks to one another are a potential cause of variations in dielectric constant. This relationship may be partly compositional, but is almost certainly structural as well. The dielectric con-

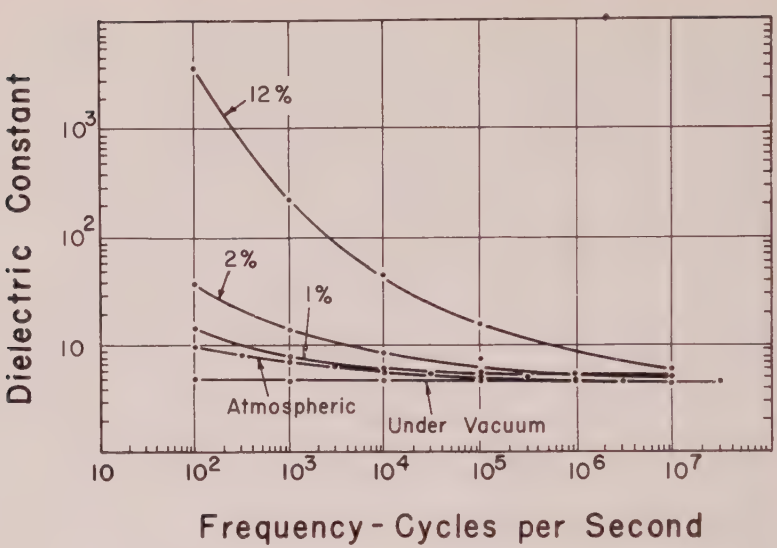


Fig. 8. Measured values of relative dielectric constant for a typical sample of Wilcox sandstone, artificially water-saturated.

stant of a rock is not generally an average of its component constituents (including the air or water filling the pores), but tends to be greater than what would be predicted by simple averaging. This increase in dielectric

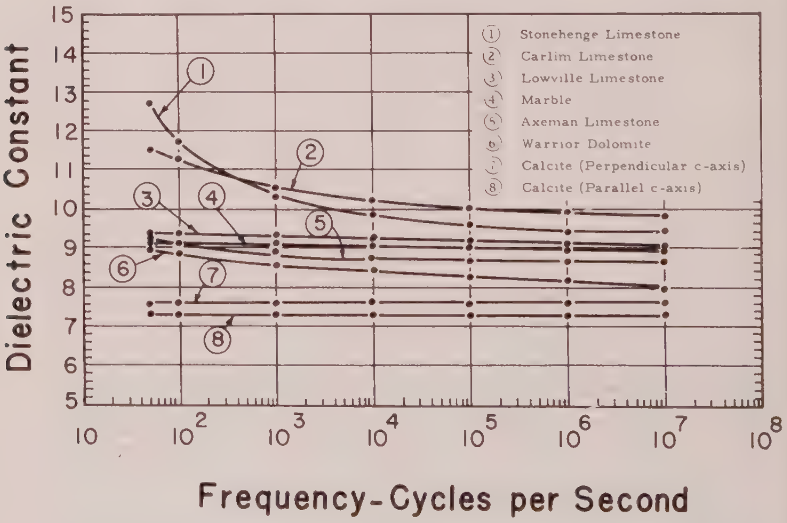


Fig. 9. Measured values of relative dielectric constant of limestones.

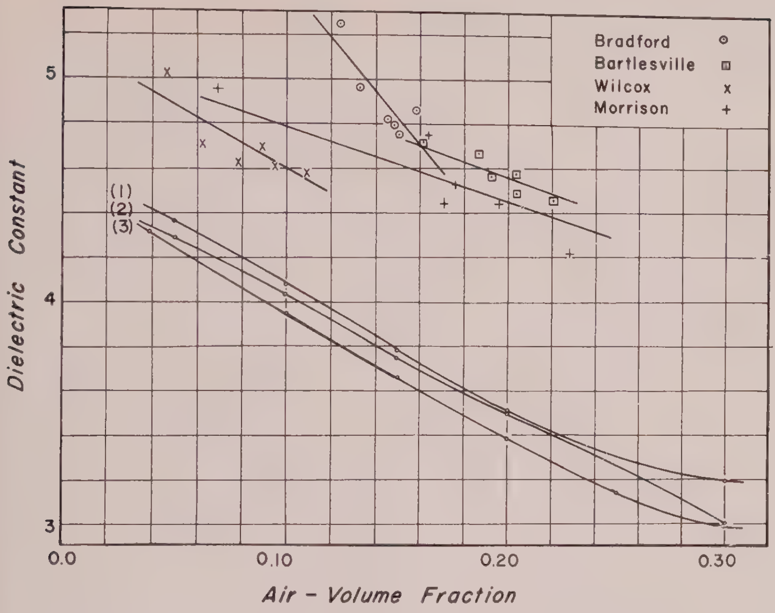


FIG. 10. Observed relative dielectric constant at 100 kc. as a function of the volume fraction of air compared to various mixing formulas.

Curve 1: $\frac{K - K_1}{3KV} = \frac{K_2 - K_1}{K_2 - 2K}$ (Bottcher, 1952, p. 417)

2: $\frac{K_2 - K}{K_2 - K_1} = (1 - V)\left(\frac{K}{K_1}\right)^{1/3}$ (Bruggeman, 1935)

3: $\mathrm{Log}_{10} K = \sum V_n \log_{10} K_n$ (Von Hippel, 1954A, p. 231, originally from Lichtenecker)

K is the dielectric constant of the mixture,
K_1 and K_2 are the dielectric constants of air and quartz, and V is the volume fraction of the quartz.

constant must be due to the interaction of the separate components present on one another.

A number of formulas have been proposed to describe the dielectric constant of simple mixtures of substances of different dielectric constant. The predictions of three of these are compared with observed values of the dielectric constants of dried sandstones at 100 kc. in Fig. 10, treating the sandstones as air-quartz mixtures. The lines through the observational data are least-squares fits. The slopes except in the case of the Bradford, a notoriously dirty sand, are roughly parallel to the predicted curves but are in all cases above them. Indeed, most of the sandstone samples studied had higher dielectric constants than pure quartz, even the relatively clay-free Wilcox.

The failure of mixing rules is even more striking in the case of wet samples at low frequencies. Water has a dielectric constant of about 80 under room conditions at the frequencies used here. (This is true for both pure and salt water, see e.g. Von Hipple 1954B.) Thus, moist rocks may have dielectric constants many times those of their separate components.

Examination of Figs. 4 through 9 will show that only in the case of minerals (and not all of them) is the dielectric constant independent of frequency. All rocks and some minerals show an increase in dielectric constant with decrease in frequency in the range studied. This is consistent with the observations of Takubo and Ukai (1954), who observed dispersion in the range 50–400 kc. to be related to the purity of the minerals they were testing. One and possibly the principal factor which causes this dispersion is the presence of moisture in the pores of the rock. When dried and held under vacuum, sandstone samples ceased to exhibit appreciable dispersion. Saturation with water caused an increase in dielectric constant. The amount of water needed to raise the dielectric constant is very small. A dried sample exposed to the air gradually increases in dielectric constant, presumably by the adsorption of moisture, even though the amount of water taken in is too small to measure by weighing the sample. A Wilcox sandstone sample which had been exposed to the air for a long time was put in the sealed dielectric-constant-measurement cell, and evacuated for five hours. The dielectric constant at 100 *cps* fell in about an hour from an initial value of 15.6 to an equilibrium value of 4.8. On reexposure to the air the dielectric constant gradually rose, taking around three hours to return the first third of the way toward its original value. Similar experiments with albite and diabase resulted in no drift in the dielectric-constant.

In the case of the various silica varieties tested, it is reasonable to suppose that the larger low-frequency dielectric constants of the chert and chalcedony specimens as compared to the intermediate novaculite and pegmatitic quartz values and lowest single-crystal value are due to the presence of varying amounts of water. Folk and Weaver (1952) have shown that the water content of cherts increases going from microcrystalline novaculite to "spongy" chalcedony.

Increased temperature had a similar effect. Heating a sample of Wilcox sandstone caused a rapid drop in dielectric constant from an initial value of 12.9 at room temperature to 5.5 at 100° C., then a slower, small decrease to a minimum of 5.1 at 200°, followed by a rise to 7.5 at 300°. The initial drop is explainable by loss of adsorbed water. The loss above

100° could be merely a time lag in the escape of the moisture, or could represent loss of a more tightly held water fraction. The whole heating cycle took about three hours. The rise in dielectric constant at the higher temperatures is possibly an effect of temperature on the freedom of atoms and dipoles to move in an electric field. A similar effect for quartz has been reported by Kiriyama and associates (1955). On cooling the dielectric constant fell to a minimum of 4.8 at 80° C. As room temperature was approached the rise with water adsorption again began.

The dependence on water content of the silica minerals has already been pointed out. The variation for minerals such as albite and rocks such as diabase (Fig. 6) cannot easily be explained by the presence of water. Evacuation did not significantly affect these minerals. Therefore, whatever the causes of the variation, it can occur for dry as well as moist materials.

High values of dielectric constant such as those observed here are not unique to this study. Evjen (1948), Fricke (1925, 1926), Dunlap and Makower (1945), Koops (1951), Von Hippel (1954B), Lombardini (1958) and others (see Keller and Licastro 1959) have observed comparable values for sediments in place, biological cell suspensions, dehydrated carrots and ferrites, respectively. These observers assume some form of interfacial polarization to be the most likely explanation of their observations.

The problem of mixed dielectrics was originally analyzed by Maxwell (1892) and extended by Wagner (1913). Consider a dielectric consisting of two sheets of materials 1 and 2 (Fig. 11*a*), each characterized by a relative dielectric constant, conductivity, and thickness, K_1, σ_1, d_1, and K_2, σ_2, d_2, respectively. Such a capacitor may be represented by the equivalent circuit shown in Fig. 11*b*. Von Hippel (1954A, 228 ff. after Maxwell 1892, Wagner 1924) has shown that a two-layer dielectric behaves as a one-layer dielectric of value:

$$K = K_\infty\left(1 + \frac{K'}{1 + \omega^2 t^2}\right) \tag{3}$$

where K_∞ is the value of dielectric constant at very high frequencies, t is the relaxation time, $\omega = 2\pi$ times the frequency and

$$K' = \frac{K_0 - K_\infty}{K_\infty} \tag{4}$$

where K_0 is the static (zero frequency) dielectric constant. From (3) and (4):

$$K = K_\infty + \frac{K_0 - K_\infty}{1 + \omega^2 t^2} \tag{5}$$

In terms of the two-layer capacitor of Fig. 11, Von Hippel has further shown that

$$K_0 = \frac{d_1 + d_2}{\dfrac{d_1}{K_1} + \dfrac{d_2}{K_2}} \left[1 + d_1 d_2 \left\{ \frac{\dfrac{1}{\sigma_1}\sqrt{\dfrac{K_1}{K_2}} - \dfrac{1}{\sigma_2}\sqrt{\dfrac{K_2}{K_1}}}{\dfrac{d_1}{\sigma_1} + \dfrac{d_2}{\sigma_2}} \right\}^2 \right] \tag{6}$$

which reduces to

$$K_0 = (d_1 + d_2) \left[\frac{K_1 d_1 \sigma_2^2 + K_2 d_2 \sigma_1^2}{(\sigma_1 d_2 + \sigma_2 d_1)^2} \right] \tag{7}$$

According to this theory, the media d_1 and d_2 may be subdivided into any number of layers without changing the dielectric response of the system, provided the volume ratios of the media are unchanged. Equation (7) can be normalized by letting $d_2/d_1 = D$ and $\sigma_1/\sigma_2 = R$, becoming:

$$K_0 = K_1(1 + D) \frac{1 + DR^2 \dfrac{K_2}{K_1}}{(1 + DR)^2} \tag{8}$$

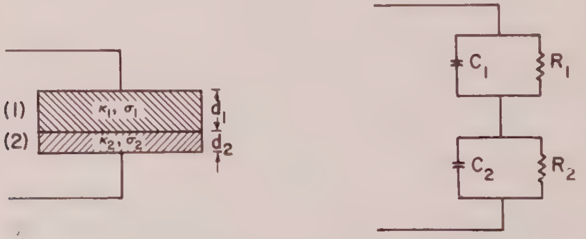
For a maximum or minimum

$$\frac{dK_0}{dR} = 2D(1 + D) \frac{RK_2 - K_1}{(DR + 1)^3} = 0 \tag{9}$$

The value $R = K_1/K_2$ corresponds to a minimum and $R = \infty$ to a maximum. When R becomes large, (8) becomes

$$K_0 \rightarrow \frac{1 + D}{D} K_2 = \frac{d_1 + d_2}{d_2} K_2 \tag{10}$$

so that K_0 is always greater than K_2. In this case, the largest values of K_0 are reached for small values of D. Small values of D by themselves will not have a strong effect.



a. Two Layer Condenser **b. Equivalent Circuit**

FIG. 11. Maxwell-Wagner model of two-component dielectric (after Von Hippel 1954A).

What this means is that material 1 must be the more conductive material (preferably strongly so) and the effect is stronger the more plentiful material 1 is. The increase in dielectric can be visualized as a result of an effective decrease in separation of the capacitor plates resulting from the presence of conducting material between them. In Fig. 11*a* it is as though the charge was shifted from the upper plate of the capacitor to the interface between the layers and the conductive σ_1-layer was shorted out.

By using the above treatment and considering the material to consist of conductive grains separated by insulating films, Koops (1951), Fairweather and Frost (1953) and Miles *et al.* (1957) were able to explain both the high values of dielectric constant and the strong dispersion of ferrites at low frequencies.

Unfortunately, this theory will not predict dielectric constants of the type observed here because conducting material is not present in sufficient quantity. If we assume the rock matrix is characterized by parameters $K_2=4.6$, $\sigma_2=10^{-6}$ mho-meters, and $d_2=0.99$, and the saturating fluid by $K_1=80$, $\sigma_1=1$ mho-meter, $d_1=0.01$ ($R=10^9$, $D=99$), K_0 will approximately equal 1.01 K_2.

The value of the Maxwell-Wagner theory is that it shows what sort of process is needed to give a high dielectric constant. We must have some mechanism which will permit a high degree of polarization along interfaces near the electrodes, and at the same time will allow free movement of charges between these polarization surfaces.

The fact that water plays such an important role in the process suggests that electrolytic conduction is involved. The fact that only small quantities of water are involved implies that the effect must somehow be enhanced over what would occur for an ordinary conductor of the type postulated in the Maxwell-Wagner theory.

Keller and Licastro (1959) have discussed the possible role of clays in acting as semi-permeable membranes in producing polarization. If positive ions were freer to move than negative ions, then a strong charge separation could result. This theory requires the presence of clays in the rock. Since dispersion is as great for the relatively pure Wilcox sand as for the others, it appears to be inadequate to explain more than a part of the observations.

Electrode polarization could have a similar effect. Electrode polarization consists of a charge accumulation along the boundaries of metallic and ionic conductors. These interfaces could be either distributed throughout the sample or containing it. In order to measure the dielectric constant, the sample was placed between metal electrodes and a field applied. As current flowed in and out of these electrodes, charges could accumulate in their vicinity producing an effect similar to the accumulation of charges on an interface within the material being studied. Such electrode polarization, if it existed, would be due to the measuring apparatus, not to the material alone.

Keller and Licastro have rejected electrode polarization as an explanation of dispersion such as was observed here because the frequency dependence of the dispersion is not what would be predicted by postulated theories of electrode polarization. This is a negative argument. Quantitatively, electrode polarization can enhance apparent capacity sufficiently to explain the observed values of dielectric constant, as Keller and Licastro pointed out. Therefore, it can not be ruled out as at least a part of the explanation. On the other hand, the fact that strong dispersion exists for materials such as chalcedony, where such water as may be present is closely confined and is not free to migrate to the electrode surfaces, argues against electrode polarization being the only effect involved. It seems more likely that the charge accumulation is a surface effect within the rock itself, probably along water covered surfaces. The presence of dispersion in such materials as bytownite and albite suggests that significant amounts of water are not needed for the effect to occur. It may be that defects within the crystal lattice are present in sufficient quantity to allow widespread minor polarization of this sort. These defects could be water inclusions, or they could be smaller irregularities.

CONCLUSIONS

From the above discussion it can be concluded that below one megacycle, the presence of moisture in a rock plays a dominating role in determining its dielectric constant. A logical explanation of this appears to be that some form of interfacial polarization is formed, possibly along crystal or rock-fragment boundaries. Dispersion can be caused in open-structured porous rocks such as sandstones, or where the water is a more integral part of the mineral structure as in the case of chert, chalcedony and pegmatitic quartz. Water is probably not necessary for dispersion in this range, as the phenomenon was observed for minerals such as bytownite as well as for various compact igneous rocks.

It is probable that the phenomenon observed here is closely related to the induced polarization on which one variety of electrical prospecting is based (see *e.g.* Marshall and Madden, 1959). Induced polarization is known to be especially prominent in the case of sulfides and of clay bodies of certain types. The work reported here indicates that it is a very general phenomenon for natural rock formations. Strong dispersion was observed even for the "pure" Wilcox sandstone.

At low frequencies dielectric constant increases with the water content of the rock. The amount of this increase is greater than would be predicted by simple mixing formulas which have been proposed in the past. This is bound to be the case inasmuch as the dielectric constant of many rocks at low frequencies exceeds the dielectric constants of any of the components of the rocks.

A great deal more data on natural rocks needs to be gathered, especially at frequencies lower than 50 cps and with 100 per cent water saturation. Without such data, perhaps even with it, laboratory determinations of the dielectric constants of individual minerals, themselves much needed, are of little help in predicting the dielectric constants of rocks under natural conditions.

ACKNOWLEDGMENTS

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REFERENCES

BATES, T. F., GRUVER, R. M., AND YUSTER, S. T. (1947) The Clay Content of Oil Sands: The Pennsylvania State College, M. I. Exp. Sta. T. P. No. 120.

BOTTCHER, C. J. F. (1952) Theory of Electric Polarization: Elsevier.

BRUGGEMAN, D. A. G. (1935) Berechnung verschiedener physikalischer Konstanten von Heterogenen Substanzen: *Ann. Phys.* **24**(5): 636–679.

CADY, W. G. (1946) Piezoelectricity: McGraw-Hill.

DEBYE, P. (1912) Einige Resultate einer Kinetischen Theorie der Isolatoren: *Physik. Zeits.* **13**(3): 97.

DUNLAP, W. C., AND MAKOWER, B. (1945) Radio Frequency Dielectric Properties of Dehydrated Carrots: *Jour. Phys. Chem.* **49**: 601–602.

EVJEN, H. M. (1948) Theory and Practice of Low-Frequency Electromagnetic Exploration: *Geophysics* **13**: 584–594.

FAIRWEATHER, A., AND FROST, E. J. (1953) Dielectric Behaviour of Magnesium Ferrites: *Proc. Inst. Elect. Engrs.* **100**(IIA): 15–22.

FOLK, R. L., AND WEAVER, C. E. (1952) A Study of the Texture and Composition of Chert: *Amer. Journ. Soc.* **250**: 498–510.

FRICKE, H. (1925) The Capacity of a Suspension of Conducting Membrane for a Current of Low Frequency: *Phys. Rev.* **26**: 678–681.

— — (1926) The Electric Capacity of Suspensions with Special Reference to Blood: *Jour. Gen. Physiol.* **9**: 137–152.

HARTSHORN, L., AND WARD, H. (1936) Measurement of Permittivity and Power Factor of Dielectrics at Frequencies from 10^4 to 10^8 Cycles per Second: *Proc. Inst. El. Eng.* **79**: 597–609.

HOLMES, C. R. (1954) Some Factors Related to the Electrical Properties of Porous Sandstones: *Producers Monthly* **19**(1): 21–27.

——— (1958) Dependence of Resistivity of Porous Sandstones on Fluid Distribution: Penn. State Univ. Ph.D. Thesis.

KELLER, G. V., AND LICASTRO, P. H. (1959) Dielectric Constant and Electrical Resistivity of Natural State Cores: *U. S. Geol. Surv. Bull.* **1052H:** 257–285.

KIRIYAMA, R., IBAMOTO, H., KOIZUMI, R., AND KITAGAKI, R. (1955) Dielectric Dispersion of Low Quartz: Sci. Rep., no. 4, South College, Osaka Univ.

KOOPS, G. C. (1951) On the Dispersion of Resistivity and Dielectric Constant of Some Semi-Conductors at Audio Frequencies: *Phys. Rev.* **83:** 121–124.

KRYNINE, P. D. (1948) Petrology and Genesis of the Third Bradford Sand: Penn State Coll. M. I. Exp. Sta. Bull. 29.

LICASTRO, P. H. (1959) Dielectric Behavior of Rocks and Minerals: Penn. State Univ. Ph.D. Thesis.

LOMBARDINI, P., AND SCHWARTZ, R. (1958) Ferrites for High-Power R-F Tuning: Elec. Mfg. 5 (Aug.).

MAXWELL, J. C. (1892) A Treatise on Electricity and Magnetism p. 452–461: Dover.

MILES, P. A., WESTPHAL, W. B., AND VON HIPPEL, A. (1957) Ferromagnetic Semi-conductors: *Rev. Mod. Phys.* **29**(3): 279–307.

MARSHALL, D. J., AND MADDEN, T R. (1959) Induced Polarization, a Study of Its Causes: *Geophysics* **24:** 790–816.

RAO, D. A. A. S. N. (1947) Dielectric Constants of Crystals: *Proc. Indian Acad. Sci.* **25A:** 408–412.

——— (1948) Dielectric Anisotropy of Rocks: *Proc. Indian Acad. Sci.* **28A:** 26–29.

——— (1949) Dielectric Constants of Crystals-III: *Proc. Indian Acad. Sci.* **30A** 82–86.

SLICHTER, L. B., AND TELKES, M. (1942) Electrical Properties of Rocks and Minerals: Geol. Soc. Am. Sp. Paper 36, p. 299–319.

SMITHSONIAN PHYSICAL TABLES (1933) 8th Ed., Smithsonian Inst.

TAKUBO, J., AND UKAI, Y. (1954) On the Dielectric Behaviours of Minerals Under the Variable Wave Frequencies: *Mineralogical Jour.* **1**(5): 253–274.

———, ———, AND KAKITANI, S. (1953) On the Dielectric Constants of Minerals: *Mineralogical Jour.* **1**(1): 3–24.

VON HIPPEL, A. R. (1954a) Dielectrics and Waves: Wiley.

——— (1954B) Dielectric Materials and Applications: Wiley.

WAGNER, K. W. (1913) Zur Theorie der Unvollkommenen Dielectrika: *Ann. Phys.* **40:** 817–855.

——— (1924) Die Isolierstoffe der Elektrotechnick: Springer.

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IMBIBOMETRY—A NEW METHOD FOR THE INVESTIGATION OF CLAYS

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Abstract

A method for rapid identification of clay minerals in natural clays or in artificial aggregates prepared by elutriation and sedimentation of clay particles is described. The behavior of a drop of water and a drop of ethylene glycol on the surface of a smoothed section is observed. The section is easily prepared on glass- and emery-cloth. The following physical properties are decisive: (1) total surface area of the particles, (2) marked swelling of montmorillonite and "open" illite and no swelling of kaolinite and "closed" illite, (3) small wettability of aggregates of the kaolinite group minerals and greater wettability of illite and montmorillonite aggregates. The speed of imbibition of the liquid by the clay aggregate is regulated by the absorption equation. The method is explained on the basis of the experimental data, obtained by the investigation of eleven clays from Central Europe.

Origin and Development of the Method

The method of observing the behavior of drops of water and of ethylene glycol on sections of unconsolidated clay rocks was worked out in our laboratory (Konta, 1956). Two polar liquids, differing considerably in their viscosity, were used.

It was expected that water and ethylene glycol would be quickly imbibed by the unconsolidated clay rocks, in which the particles of clay minerals are large and thick. The imbibition ought to be slower for aggregates in which the clay particles are rather small and thin. The less viscous water should be imbibed more quickly and cause a greater intermicellar swelling of montmorillonite clays than the more viscous ethylene glycol. During the experimental work it was found that in addition to the speed of imbibition and the extent of swelling, a further highly important diagnostic property of clay aggregates was noted, namely the wettability.

Until now no special name has been given to the new method (Konta, 1959 *a*,*b*). In the present paper there is applied to this new method the name of *imbibometry*. The investigation of water and ethylene glycol imbibition on sections of unconsolidated clay aggregates can be quantitatively measured and is reliable for the rapid identification of clay minerals. Besides, this method has a wider use in the investigation of some clay-rock properties which are important in geology and technical practice.

Basis of the Method

The method is based on certain physical properties of clay minerals and clay aggregates in the presence of polar liquids. They are:

(1) The total surface area of the particles.
(2) Marked swelling of montmorillonite and "open" illite and none for kaolinite and normal illite.
(3) Wettability of the aggregates.

These physical properties become apparent simultaneously during the imbibition of a drop of water or a drop of ethylene glycol on sections of clay aggregates and therefore it is necessary to observe and record simultaneously the phenomena caused by all three properties.

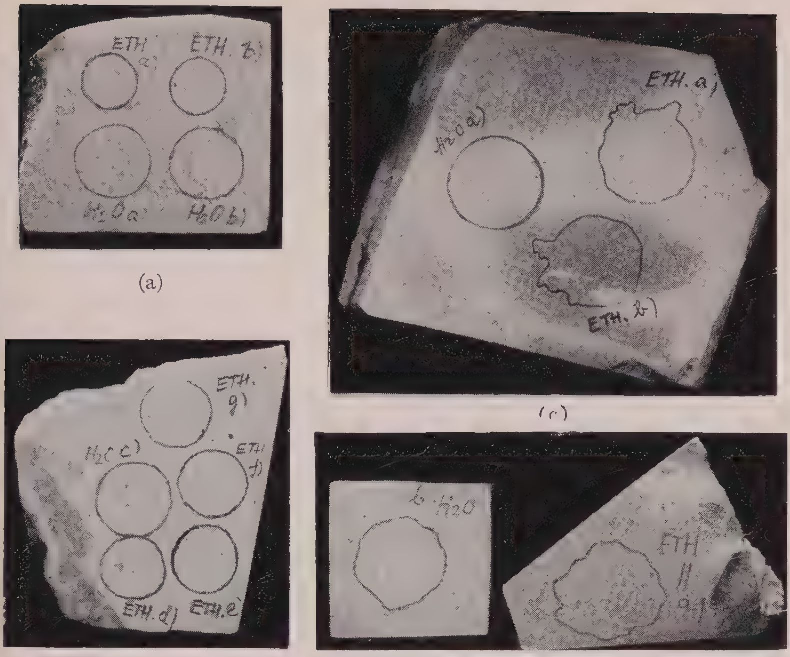
The *total surface area* of the clay particles is fully characteristic for each chief group of clay minerals and is the chief physical property affecting the speed of imbibition of a drop of water and of ethylene glycol by the surface of the clay sections. Crystals of the kaolinite group minerals, which form the thickest plates of all the clay minerals, have the smallest total surface area, usually in several $m.^2/g.$ up to several tens $m.^2/g.$; their highest value reaches about 40–60 $m.^2/g.$ Minerals of the illite group have crystals essentially thinner and a total surface area several times larger, usually in many tens $m.^2/g.$ most often from 70 to 150 $m.^2/g.$; and "open" illite more than 200 or 300 $m.^2/g.$ Finally, minerals of the montomorillonite group have the thinnest crystals and their total surface area is usually in hundreds $m.^2/g.$, most often between 500 $m.^2$ and 800 $m.^2/g.$

The *swelling* of montmorillonite and of "open" illite (van der Marel 1960) makes possible a quick and easy determination of the presence of these minerals in a clay. It is necessary, while applying the imbibometric method, to note on the sections of the clay not only the swelling itself but also the speed of imbibition (in seconds) and the wettability.

The *wettability* of unconsolidated but coherent aggregates of clay minerals represents a very important property and makes it possible to distinguish the kaolinite clays from illite and montmorillonite. Kaolinite clays have the smallest wettability. On sections of kaolinite, a drop of water or ethylene glycol always takes up a relatively small circular area (Fig. 1 *a*,*b*). On illite (Fig. 1 *c*,*d*) or on montmorillonite (Fig. 2) a drop of water or ethylene glycol spreads over a considerably larger area. When ethylene glycol is used, and in some cases even with water, characteristic small spurs are formed. The imbibition ratio is the area occupied by one drop of ethylene glycol divided by the corresponding area for water. This ratio is less than 1 for kaolinite, but always above 1 for illite, and especially so for montmorillonite.

MATHEMATICAL EXPRESSION

The rate of imbibition depends both on the physical properties of the clay aggregate and on the character of the liquid. The purity of the



(a) (c) (b) (d)

FIG. 1. (a) Characteristic small circular areas taken by drops of water and of ethylene glycol. Kaolin from Sedlec near Karlovy Vary, western Bohemia.

(b) Silty kaolinite clay from Jarov near Plzeň, western Bohemia.

(c) Greater areas taken up by a drop of water and a drop of ethylene glycol, with characteristic small spurs if ethylene glycol is used. Illite clay from Chlum near Beroun, central Bohemia.

(d) Greater areas taken up by a drop of water and a drop of ethylene glycol, with characteristic small spurs. Illite clay from Füzerradvany, Hungary.

liquid, and the temperature can be controlled, and atmospheric pressure should be normal.

The speed of imbibition of the liquid by the clay aggregate is regulated by the absorption equation:

$$t = \frac{s \cdot \eta}{\epsilon^3 \cdot \sigma \cdot k} \left(\frac{q}{A}\right)^2,$$

where:

t = the time of the complete imbibition of the liquid in seconds,

s = the effective surface area of mineral particles (in $\mathrm{cm}^2/\mathrm{cm}^3$ of the substance),

η = the viscosity (in poises at 20° C.),

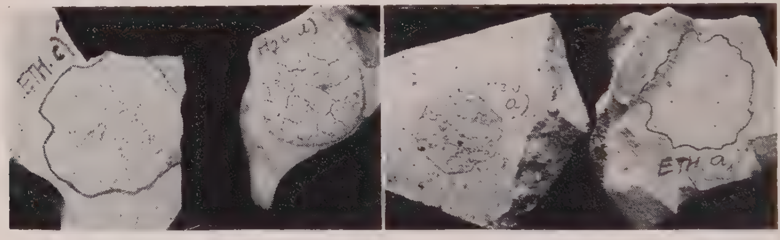
ϵ = the effective porosity (in %:100),

σ = the surface tension of the liquid (in dynes cm^2; in the value the gravity acceleration is, therefore, included),

k = the constant including the shape of the particles and the tortuosity of pores in the clay aggregate (in the majority of clays its value remains constant; it depends, however, on the direction of imbibition, i.e. whether it is for instance parallel or perpendicular to the lamination of the rock),

q/A = the amount of the liquid (q in cm^3) sorbed on the area (A, in cm^2) during a known time.

An analogous equation has been used to express the sorption property of hardened Portland cement paste (Powers and Brownyard, 1948).



(a) (b)

FIG. 2 (a) Swollen areas taken up by a drop of water (right) and ethylene glycol (left). Montmorillonite clay from Istenmezö, Hungary. (Sample No. 10.)

(b) Swollen area after imbibition of a drop of water (left) and less evident swelling on bentonite section if ethylene glycol is used (right). Braňany near Most, northern Bohemia. (Sample No. 9.)

From this equation it follows that for the imbibition rate of a known constant amount of polar liquid on a known area and under a constant temperature and constant conditions of purity of the liquid, as well as an unchanging direction of the imbibition, only two properties of clay are decisive, namely, the total surface area of the particles (s) and the effective porosity (ϵ). The time of imbibition of the liquid by a clay aggregate is in direct proportion to the effective surface area of the particles and inversely proportional to the effective porosity of this aggregate.

The *effective porosity* of the clay aggregate is a further important physical property which also has an influence on the imbibition speed of the liquids, as follows from the equation given above. In the majority of unconsolidated, yet coherent kaolinite and illite clays, the values of the effective porosity varies between 25 50% under laboratory conditions of humidity and temperature. In montmorillonite rocks the effective porosity is still smaller, usually between 10–20% under laboratory humidity and temperature conditions. The experimental work has shown that the imbibition speed on the sections of clays of different mineral composition is mainly influenced by the total surface area of the particles, which value varies with the chief groups of clay minerals, *i.e.* kaolinite, illite and montmorillonite. The differences in the speed of the imbibition of liquids by clays of approximately identical mineral composition and of not considerably different values of the total surface area of the particles, are mainly caused by differences in effective porosity.

This important finding is represented by several diagrams drawn up on the basis of data obtained from the study of eleven samples of unconsolidated clay rocks of different mineral composition. The approximate quantitative mineral composition of these rocks had been given in the author's articles (Konta, 1959 *a,b*). Since the values obtained are necessary for the understanding of the following four figures, they will be repeated here in the abbreviated form of a triangular diagram (Fig. 3).

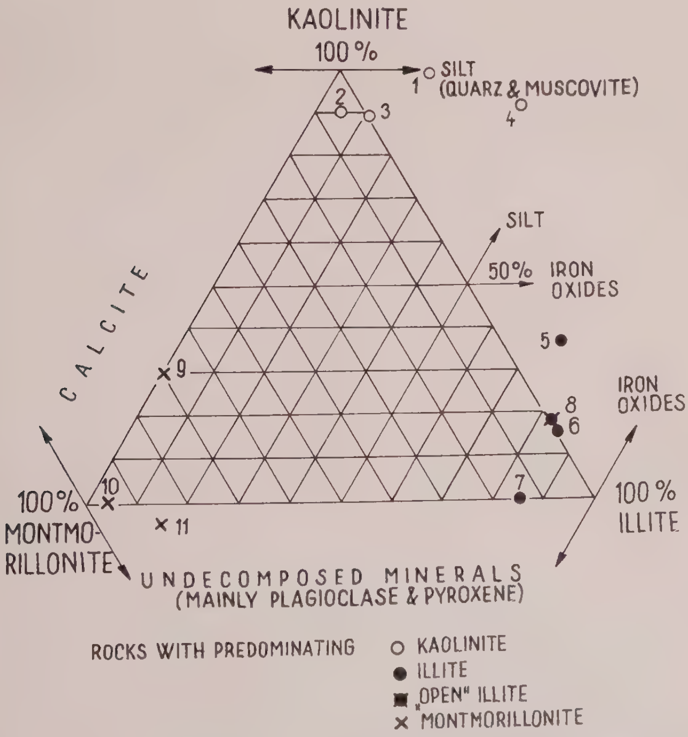


Fig. 3. The approximate semiquantitative mineral composition of eleven clay rocks studied. The data were obtained by evaluation of the results of these methods: investigation under polarizing microscope, *x*-ray analysis, DTA, gravimetric thermal analysis and imbibometry. The numbers of the points in the triangular diagram correspond to the numbers in all other diagrams and tables.

In Table I, data are given concerning the effective porosity, density and the total surface area of the particles of eleven samples investigated. The last values have been found by the absorption method according to Dyal and Hendricks (1950), namely in all cases with finely powdered samples sieved through 200 mesh with aperture of 0.074 mm.

In Fig. 4 the values of effective porosity expressed in $(\%:100)^3$ are given. On the horizontal axis, the times during which one drop of water is imbibed by the sections are plotted. The times found are related to a uniform basic area (cf. Konta, 1959 *a*,*b*). The method of calculating of the imbibition times are illustrated in Tables II and III. Figure 5 is similar to Fig. 4, but for ethylene glycol. Here too, the values of the imbibition times have been related to a uniform basic area.

From Figs. 4 and 5 this main conclusion follows: The effective porosity has little decisive influence upon the speed of imbibition of water and ethylene glycol by the unconsolidated but coherent clay aggregates. However, in samples of nearly identical mineral composition, which do not differ greatly in the values of the total surface area of the particles, the differences in effective porosity have a marked influence upon the speed of imbibition. This can be best seen in kaolinite clays.

In addition to the effective porosity and the total surface area of the

TABLE I. EFFECTIVE POROSITY, DENSITY AND TOTAL SURFACE AREA OF ELEVEN CLAY SAMPLES

Sample	Effective porosity (approximate data)	Total surface in m.^{2}/g.	Densities of samples dried at 110° C.	Total surface in cm.^{2}/cm.^{3} $\times 10^4$
Kaolinite clays				
1. Vonšov-Nová Ves, w. Bohemia	43.8	41.1	2.64	108.50
2. Staré Sedlo near Loket, w. Bohemia	31.5	45.5	2.59	117.85
3. Sedlec near Karlovy Vary, w. Bohemia	37.0	33.9	2.68	90.85
4. Jarov, near Plzeň, w. Bohemia	35.5	58.5	2.68	156.78
Illite clays				
5. Chlum, near Beroun, c. Bohemia	33.6	79.3	2.75	218.08
6. Chlum, centr. Bohemia	35.1	72.7	2.70	196.29
7. Füzerradvany, Hungary	44.4	148.8	2.78	413.66
Clays with predominating montmorillonite and "open" illite				
8. Vonšov near Cheb, w. Boh.	13.8	358.2	2.83	1013.71
9. Braňany near Most, n. Bohemia	17.7	348.7	2.75	958.93
10. Istenmezö, Hungary	19.6	730.0	2.60	1898.00
11. Komloska, Hungary	11.4	667.5	2.80	1869.00

particles, another important factor appears in montmorillonite clays or in clays containing the "open" illite, which considerably influences the speed of imbibition of the polar liquids into the sections. This important factor is the phenomenon of swelling. Especially during imbibometric tests with water such a strong swelling takes place, that immediately after the contact of water and clay on the surface of a polished section the original effective porosity grows several times. This is the cause of a considerably quicker imbibition of water than would correspond only to the value of the effective porosity of the aggregate and the total surface area of the particles (cf. Fig. 4). An especially strong swelling took place in both the montmorillonite rocks from Hungarian localities.

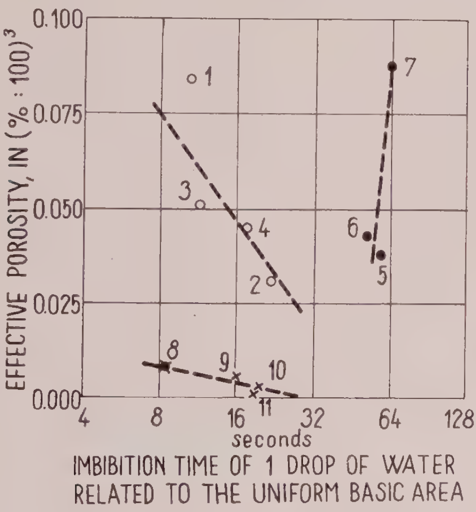


FIG. 4. Dependence between effective porosity and imbibition speed of one drop of water.

The relation between the total surface area of the clay particles and he speed of imbibition of water and ethylene glycol are shown in Figs. and 7. In Table I, in the fourth column are given the values of the total urface area of eleven clay rocks investigated, expressed in cm.^{2}/cm.^{3} of he substance $\times 10^4$. From these figures this main conclusion follows: The speed of imbibition of a drop of water and ethylene glycol by sections of unconsolidated clay rocks is chiefly determined by the value of the total surface area of the particles. The other physical properties of clay particles and their aggregates are of smaller import. This is only valid for the use of polar liquids with nonswelling or slightly swelling clays. In strongly swelling clays, instead of remaining constant, the ef-

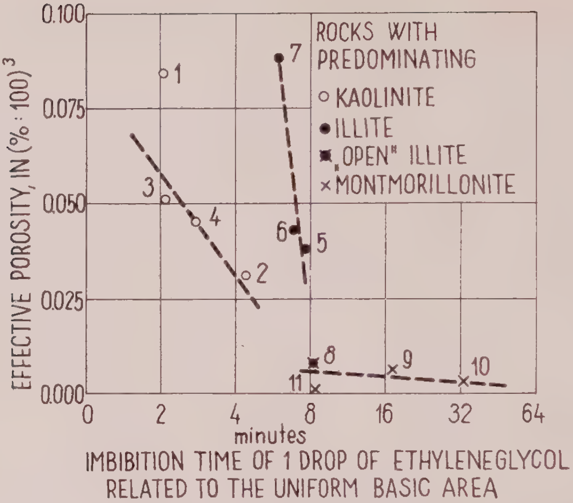
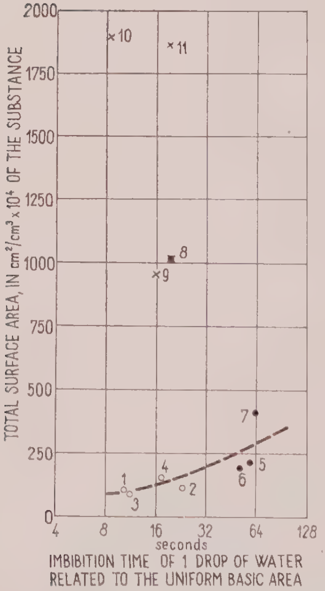


FIG. 5. Dependence between effective porosity and imbibition speed of one drop of ethylene glycol.



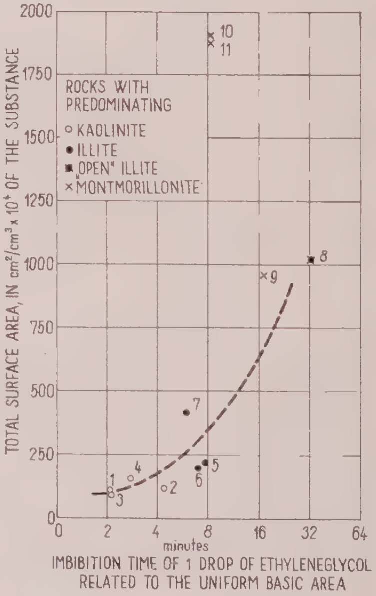


FIG. 6. (left) Dependence between total surface area and imbibition speed of one drop of water.

FIG. 7. (right) Dependence between total surface area and imbibition speed of one drop of ethylene glycol.

TABLE II. CALCULATION OF THE RESULTANT IMBIBITION TIME OF A DROP OF WATER AND A DROP OF ETHYLENE GLYCOL ON THE POLISHED SECTION OF THE NATURAL KAOLIN FROM SEDLEC NEAR KARLOVY VARY, BOHEMIA

	Real area occupied by a drop, in mm.^{2}	Recorded imbibition time, in seconds	$\frac{\text{Real area}}{\text{Uniform basic area}}$	Resultant imbibition time, in seconds
Water:				
(*a*)	85	13	$\frac{85}{89}=0.955$	$0.955\times13=12$ sec.
(*b*)	102	10	$\frac{102}{89}=1.146$	$1.146\times10=11$ sec.
(*c*)	91	12	$\frac{91}{89}=1.022$	$1.022\times12=13$ sec.
(*d*)	80	14	$\frac{80}{89}=0.899$	$0.899\times14=13$ sec.
	358:4=89 mm.^{2}, is the uniform basic area			Average=12 sec.
Ethylene Glycol:				
(*a*)	56	121	$\frac{56}{55}=1.018$	$1.018\times121=123$ sec.
(*b*)	59	134	$\frac{59}{55}=1.073$	$1.073\times134=144$ sec.
(*c*)	55	119	$\frac{55}{55}=1$	$=119$ sec.
(*d*)	59	115	$\frac{59}{55}=1.073$	$1.073\times115=123$ sec.
(*e*)	55	139	$\frac{55}{55}=1$	$=139$ sec.
(*f*)	53	127	$\frac{53}{55}=0.964$	$0.964\times127=122$ sec.
(*g*)	55	135	$\frac{53}{55}=0.964$	$0.964\times135=130$ sec.
(*h*)	53	133	$\frac{55}{55}=0.964$	$0.964\times133=128$ sec.
	443:8=55 mm.^{2}, is the uniform basic area			Average=129 sec.

ective porosity on the surface of the section is increased many times vith a polar liquid, and hence the liquid imbibes rather quickly. There- ore it is necessary for the determination of the effective surface area of

TABLE III. CALCULATION OF THE RESULTANT IMBIBITION TIME OF A DROP OF WATER AND A DROP OF ETHYLENE GLYCOL ON THE SMOOTHED SECTION OF KAOLINITE CLAY FROM JAROV NEAR PLZEŇ, BOHEMIA

	Real area occupied by by a drop, in mm.^{2}	Recorded imbibition time, in seconds	$\frac{\text{Real area}}{\text{Uniform basic area}}$	Resultant imbibition time, in seconds
Water:				
(*a*)	96	16	$\frac{96}{89}=1.079$	$1.079\times16=17$ sec.
(*b*)	95	17	$\frac{95}{89}=1.067$	$1.067\times17=18$ sec.
(*c*)	89	17	$\frac{89}{89}=1$	$1\times17=17$ sec.
(*d*)	99	18	$\frac{99}{89}=1.112$	$1.112\times18=20$ sec.
				Average = 18 sec.
Ethylene Glycol:				
(*a*)	68	151	$\frac{68}{55}=1.236$	$1.236\times151=187$ sec.
(*b*)	75	111	$\frac{75}{55}=1.364$	$1.364\times111=151$ sec.
(*c*)	78	124	$\frac{78}{55}=1.418$	$1.418\times124=176$ sec.
(*d*)	65	134	$\frac{65}{55}=1.182$	$1.182\times134=158$ sec.
(*e*)	71	131	$\frac{71}{55}=1.291$	$1.291\times131=169$ sec.
(*f*)	72	120	$\frac{72}{55}=1.309$	$1.309\times120=157$ sec.
(*g*)	77	129	$\frac{77}{55}=1.400$	$1.400\times129=181$ sec.
(*h*)	88	131	$\frac{88}{55}=1.600$	$1.600\times131=210$ sec.
(*i*)	87	121	$\frac{87}{55}=1.582$	$1.582\times121=191$ sec.
				Average = 176 sec. = 2 min. 56 sec.

the particles or of the effective porosity to use nonpolar liquids. For the purpose of identification of clay minerals, the procedure of the imbibometric method here described, has proved to be a fully satisfactory one.

PREPARATION OF SECTIONS

The clay is roughly ground by circular movements on glass-paper no. 50, and then the surface of the section is smoothed on emery-cloth no. 240 or finer. Thus the preparation of a section requires no more than 2–4 minutes. By using the same type of emery cloth sections of equal quality can be obtained.

During the preparation of sections it is important to observe the following rules:

(1) The grinding is always done in dry state.

(2) Sections which should serve for the identification of clay minerals or for the determination of the relative age of clay rocks are always made parallel to the stratification. In clay aggregates without stratification a number of sections should be prepared, and in various directions.

(3) On the section or in the area where the liquid is imbibed, there should be no pores or cracks visible by eye or by lens.

(4) When the grinding is finished it is necessary to remove carefully the loosened clay powder on the surface of the polished section by means of a soft brush.

(5) The surface of the prepared section is always dull and it should not glisten in any case (as required by metallographic microscopy).

(6) The surface of the section must be free from grease.

For other purposes sections can be made perpendicular to the stratification, or with varying orientations.

Smooth sections of sandy or silty-sandy clays are for the most part difficult to prepare. For imbibometric identification of clay minerals in these rocks it is necessary to prepare artificial solid plates, by elutriation and sedimentation of dispersed particles. The natural sample of the rock is pulverized and elutriated in a tall beaker filled with water. After thorough stirring and dispersion of clay particles, adding a suitable dispersive solution, the suspension in the beaker is left to settle in a quiet place. Care must be taken so that the orientation of clay particles is not changed during the drying of the sediment. The dried sediment ready for the preparation of the section has the form of a solid disc about $\frac{1}{2}$ to 1 cm. thick.

IMBIBOMETRIC TESTS

The working process during imbibometric tests is quite simple:

(1) The section is fixed on plasticine in a horizontal position.

(2) On the surface of the polished section a drop of water is dropped from a vertically held pipette (constant size) from a height of about 4 to 6 mm. Simultaneously, we observe and ascertain:

(*a*) The size and the shape of the area occupied by the drop.
(*b*) The time during which the drop gets entirely imbibed.
(*c*) The changes on the surface of the section during the imbibition and mainly after the imbibition of the liquid.

(3) This complex observation must always be carefully registered, and the area in which the drop was imbibed, copied on a transparent paper.

Then the same process is used in the case of a drop of ethylene glycol, which is more viscous and is imbibed by all aggregates more slowly than water. It is recommended that all the observations be entered in a card index.

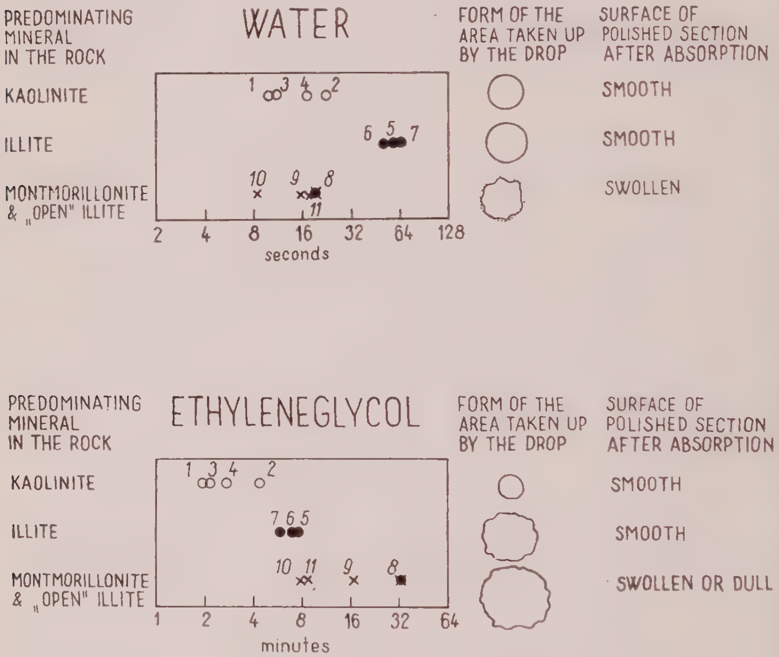


FIG. 8. Identification table serving for entering observations obtained during the imbibometric tests.

THE USE OF IMBIBOMETRY FOR IDENTIFICATION OF CLAY MINERALS

The relation of the size of the area occupied by the drop on the section to the speed of imbibition is best evident from the mathematical equation previously given. The larger the area occupied by the drop, the shorter is the time of imbibition. Every area on the section occupied by the drop is carefully traced on a transparent millimeter-lined paper and thus its size is ascertained with relative precision. Even quicker is the determination of the size of the irregularly shaped area by a suitable planimeter.

The actual measured time of a complete imbibition of a drop of water and a drop of ethylene glycol has then to be transferred to a uniform basic area and the resultant imbibition time is obtained. It is the time during which the drop should be imbibed if it occupied on every section such an area as it occupies on the section of the natural pure kaolin from Sedlec near Karlovy Vary, Bohemia. A drop of water let down from the pipette from the height of 4–6 mm. on the natural pure kaolin from Sedlec near Karlovy Vary occupies a circular area of average size 89 mm.^{2} (computed from four measurements). A drop of ethylene glycol under the same conditions occupies an area of average size of 55 mm.^{2} (computed from eight measurements). In Table II the manner of calculation of the resultant imbibition times for the pure kaolin sample from Sedlec is given. In both cases the measured values are related to a uniform basic area for water and ethylene glycol. In Table III the calculation for the section of silty kaolinite clay from Jarov near Plzeň, Bohemia, is given.

The resultant values giving the imbibition times are entered in a table (Fig. 8). In the upper part of the table the resultant imbibition times of a drop of water related to a uniform basic area with regard to the wettability and to the surface change of the section after imbibition are entered. In the lower part the corresponding times for ethylene glycol are listed.

ANOMALOUS SHORTENING OR PROLONGATION OF THE IMBIBITION TIME

In some cases the imbibition speed of water and ethylene glycol may be essentially shorter or longer than might be expected, considering the clay minerals present in the sample. The character of the predominating clay mineral can be determined, however, on the basis of mere wettability, and swelling or nonswelling of the sample. These properties can be recognized on the *smoothed* section by the different size of the area occupied by a drop of water or a drop of ethylene glycol, further by a characteristic contour of the area, and finally by a change of the surface of the polished section upon imbibition.

The *shortening* of the imbibition time of the liquid which does not correspond to the size of the effective surface area of the clay particles can be the result of different factors. Of these the most important are:

(*a*) Presence of a greater number of clastic grains.
(*b*) Swelling of montmorillonite or of "open" illite.
(*c*) Placing drop in the direction of the preferred orientation of the clay particles in samples without evident stratification.
(*d*) Presence of admixture of carbonate minerals.

(*e*) Presence of soluble salts, especially of halite.
(*f*) Formation of cracks on the section during imbibition.

The *prolongation* of the imbibition time of the liquid is most often influenced by:

(*g*) A greater consolidation of the clay rock and a total porosity under 25 per cent.
(*h*) Presence of finely dispersed organic substance (enlargement of the effective surface area).

It is therefore always important before and in the course of imbibometric tests to determine for every rock studied if the imbibition will be influenced by some of these factors. The majority of these unfavorable factors can be eliminated in imbibometry by the making of artificial solid plates of the clay. Thus can be eliminated the factors given above under *a*, *c*, *d*, *e*, and *g*.

General Use of Imbibometry

First, it is possible to identify clay minerals on sections of unconsolidated but coherent clay aggregates by a drop of water and of ethylene glycol. These aggregates can be either natural, or artificial if the natural clay is not suitable for the making of the section required. It is further possible to determine, imbibometrically, the value of effective porosity, if the total surface area of the particles is determined beforehand (*e.g.*, by a simple method according to Dyal and Hendricks, 1950). By means of imbibometry it is possible in clays to determine the direction of the maximum imbibition by making sections of various orientations. Imbibometry also quickly reveals the extent of swelling in argillaceous rocks containing montmorillonite or "open" illite. The results are of relative nature only when using polar liquids. When using a polar and a nonpolar liquid on the same section the results begin to have a quantitative character.

The imbibometric method can also, in some cases, be applied to problems connected with the determination of the relative age of clay rocks in a definite uniform geologic area. In clay rocks of relatively earlier geologic age the suitable liquid will imbibe more slowly than into later rocks which in most cases are less consolidated, *i.e.* of greater total porosity. At the same time, the mineral composition of clay rocks must be approximately the same.

On the basis of recent experimental work we can say that in the future other liquids, polar and nonpolar, will be used in imbibometry.

Acknowledgments

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References

DYAL, R. S., AND HENDRICKS, S. B. (1950): Total surface of clays in polar liquids as a characteristic index. *Soil Sci.*, **69,** 421–432.

KONTA, J. (1956): Schnelle petrographische Identifikation der Tonminerale in den Anschliffen mittels Wasser und Ethylenglykoll. *Chemie der Erde*, **18,** 179–193.

——— (1959*a*): Porosity of clay rocks and their imbibition capacity. *Silicates Industriels*, **24,** 133–136 (Bruxelles).

——— (1959*b*): Porosita a nasákavost nezpevněných jílovitých hornin. (Porosity and imbibition capacity of unconsolidated clay rocks.) *Acta Univ. Carolinae, ser. Geologica*, 25–43 (Praha).

MAREL VAN DER, H. W. (1960): Verband tussen het uiterlijk van de kleideeltjes en de grondmechanica. *LGM Mededelingen, Orgaan van het Laborat. voor Grondmechanica*, **4,** p. 1–28. (overdruk).

POWERS, T. C., AND BROWNYARD, T. L. (1948): Studies of the physical properties of hardened Portland cement paste. Auth. reprint from *Journ. Amer. Concr. Inst., Michigan*, 101–992. (*Portland Cement Assoc., Bull.* **22,** Chicago.)

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AN ABNORMAL EFFECT IN DIFFERENTIAL THERMAL ANALYSIS OF CLAY MINERALS

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ABSTRACT

If in differential thermal analysis the differential thermocouple is arranged radially through the center of an uncovered cylindrical sample holder, a spurious endothermic effect can be produced in the low-temperature region of curves of vermiculite (and of montmorillonite) when the amount of sample is reduced below a certain limit. No such peak occurs when the sample is covered with a lid or when the differential thermocouple is arranged along the axis of the sample holder with its bead at the center. The origin of the peak is investigated and it is shown how this depends on the experimental conditions and the clay mineral structure.

INTRODUCTION

In differential thermal curves of many samples of vermiculite examined at the Division of Building Research an extra low-temperature endotherm has been revealed. Such a peak has also been reported in the literature by Mielenz, Schieltz and King (1954). It occurs, in the experience of the authors, when the weight of vermiculite in the sample holder of the differential thermal equipment is reduced below a critical value (less than about half that required to fill the holder); it will frequently occur in samples of hydrobiotite that are naturally low in vermiculite. Since the extra endothermic peak has no counterpart in weight-loss curves (Mielenz, Schieltz and King 1954, and Cole, unpublished data) and can have no structural significance (Walker and Cole 1957), it has been of interest to discover why it occurs.

EXPERIMENTAL

The following materials were used in the investigation: a vermiculite from Valpy Claims, West Suk, South Africa; hydrobiotite from Libby, Montana; halloysite from Southern Indiana; sodium montmorillonite from Wyoming; gypsum from Kangaroo Island, South Australia.

Differential thermal analyses were made with the equipment described by Carthew and Cole (1953) in which the differential thermocouple is placed radially through the center of the cylindrical sample holder (Fig. 1A). The sample block is a metal cylinder (originally in stainless steel but now in nickel) $1\frac{5}{8}$ in. diameter and $\frac{15}{16}$ in. high. In it are drilled four flat-bottomed holes $\frac{3}{8}$ in. diameter and $\frac{5}{8}$ in. deep. Two of these holes, diametrically opposite each other, are used to hold the sample and reference material, respectively. The differential thermocouple wires are

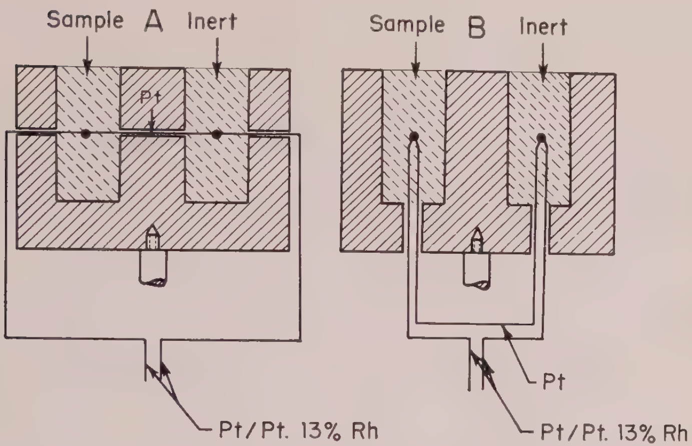

FIG. 1. A. Differential thermocouple arranged radially through the center of the cylindrical sample holder as in the equipment described by Carthew and Cole (1953).

B. Differential thermocouple arranged along the axis of the cylindrical sample holder with its bead at the center as in more conventional units (Mackenzie and Mitchell, 1957).

Pt/Pt.13%Rh of 0.5 mm. diameter. The sample holder contains about 0.8 gm. of material when lightly tamped and pressed finger tight. The heating rate is controlled at 10° C. per minute and the differential thermocouple voltage can, after amplification, be recorded at three levels; namely 100, 200 or 400 microvolts full scale deflection of the recording pen. Most of the present work was carried out on the 100 and 200 microvolt ranges. Analyses were also made with this equipment modified so that the differential thermocouple was placed along the axis of the cylindrical sample holder, with its bead at the center (Fig. 1B) as in more conventional units (Mackenzie and Mitchell, 1957). It should be noted that Carthew and Cole (1953) described their equipment as possessing a stainless steel lid to cover the block during analysis so as to screen the sample and reference material from direct radiation from the furnace tube at high temperatures. However, over the years the use of the lid has been discontinued. In this study it has been found that, at low furnace temperatures, the presence or absence of the lid is important for the effect to be described.

DILUTED SAMPLES

The effect investigated is illustrated in Fig. 2, which shows differential thermal curves produced by varying weights of vermiculite; the differential thermocouple being radially arranged and there being no covering lid to the sample holder. It is seen that when the weight of vermiculite is reduced to 25% of that required to fill the sample holder an inflection at

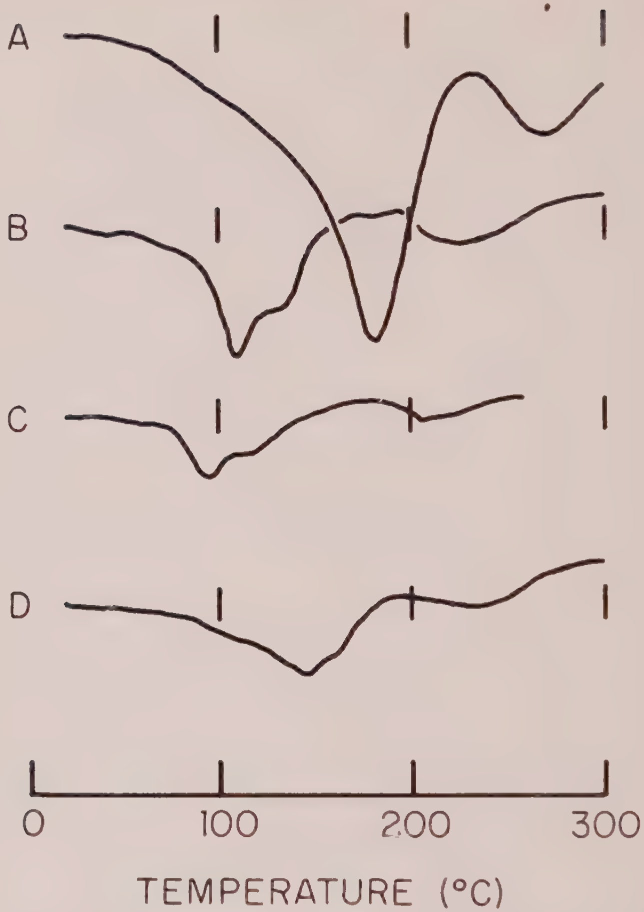

FIG. 2. Differential thermal curves of vermiculite and hydrobiotite produced by the equipment described by Carthew and Cole (1953) and run under the following conditions:

A. Vermiculite (0.8 g.) filling the whole of the sample holder.
B. Vermiculite (0.2 g.) mixed with alumina so as to fill the whole of the sample holder.
C. Vermiculite (0.1 g.) mixed with alumina so as to fill the whole of the sample holder.
D. Hydrobiotite (0.8 g.) filling the whole of the sample holder.

about 140° C. (B, Fig. 2) is apparent in the main low-temperature endotherm of the undiluted vermiculite (A, Fig. 2). Dilution to $12\frac{1}{2}\%$ accentuates the effect (C, Fig. 2). The differential thermal curve of a sample of hydrobiotite (D, Fig. 2) demonstrates a similar effect in a sample low in vermiculite (the vermiculite:biotite ratio of this sample is 1:3, Cole and Hosking, 1957). An extra endothermic peak can also be produced in the low-temperature region in samples of sodium montmorillonite (Wyoming bentonite) by similarly reducing the amount of the sample in the sample holder by dilution with inert material; the effect is thus not restricted to vermiculite.

The effect is *not observed* when differential thermal curves of diluted vermiculite are made with the *sample covered by a lid* or with equipment in which the differential thermocouple is arranged *along* the axis of the sample holder.

Sample Position and Thermocouple Arrangement

Since an extra endothermic peak can be induced by dilution of the sample for a particular arrangement of the differential thermocouple, it seems reasonable to expect that the disposition of the sample with respect to the thermocouple and the thermocouple arrangement must result in different thermal effects at the thermocouple bead. Consequently, a study was made of the influence on the differential thermal curve of placing samples of vermiculite, halloysite and gypsum in separate runs, above and below the differential thermocouple when this was arranged radially and along the axis of a cylindrical sample holder. The results in Fig. 3 show that:

(1) No matter how the thermocouple is arranged, the peak temperature is higher when the sample is below the thermocouple than when it is above; the difference is greater for a radial arrangement;

(2) When the thermocouple is arranged along the axis of the sample holder, the peak is sharpest and its area greatest when the sample is below the thermocouple; when the thermocouple is arranged radially the area of the peak is not greatly dependent upon the position of the sample but the peak is sharpest when the sample is placed above the thermocouple;

(3) When the differential thermal curves of vermiculite made with the sample below and above the thermocouple are compounded, an extra peak is introduced when the thermocouple is arranged radially (A, Fig. 3) but not when it is arranged along the axis of the sample holder (B, Fig. 3). The origin of distortions in the differential thermal curves of halloysite and gypsum, when these are made with the thermocouple arranged radially, also becomes apparent from the compounded curves.

Observations (1) and (2) have been verified in a further set of experiments in which the peak area and peak temperature have been measured for the two thermocouple arrangements for a small amount of vermiculite (~0.2 gm.) bounded by alumina and placed at various positions in the sample holder, between top and bottom. The results are plotted in Fig. 4. Observation (1) above follows from the plot of peak temperature against sample position. Observation (2) above follows from the plot of the peak area per unit weight against sample position. It is not clear why in Fig. 4 the results from position 3 are lower than those from positions 2 and 4. This anomaly does not affect the above observations.

SAMPLE LID

It has previously been stated that when the sample is covered by a lid the abnormal effect is eliminated. This is because, when a lid is used,

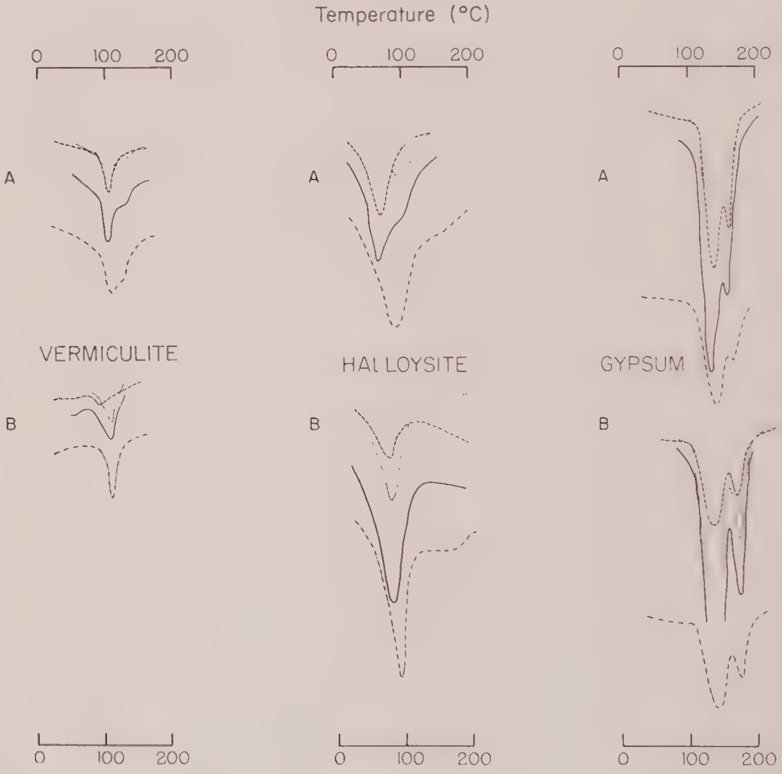

FIG. 3. Differential thermal curves of vermiculite, halloysite and gypsum as follows:

A. Differential thermocouple arranged radially through the center of the cylindrical sample holder as in Fig. 1A.

B. Differential thermocouple arranged along the axis of the cylindrical sample holder as in Fig. 1B.

- - - - Sample (about 0.2 g.) mixed with alumina to occupy fully the upper half of the sample holder (1).

······ Sample (about 0.2 g.) mixed with alumina to occupy fully the lower half of the sample holder (2).

——— Curve compounded from (1) and (2).

-·-·-· Sample (about 0.4 g.) mixed with alumina to occupy all the sample holder.

there is no longer a difference in temperature between the dehydrations of the sample from different parts of the block as was demonstrated to exist in Fig. 4 for an uncovered sample holder. This was verified in a separate experiment in which, for the radial thermocouple arrangement, the presence of a lid resulted in an increase by 30° C. in the temperature at which a 0.2 g. sample of vermiculite at the top of the sample holder (position 7, Fig. 4) dehydrated endothermically.

REMARKS

When in differential thermal analysis the differential thermocouple is arranged radially across the center of an *uncovered* sample holder, an extra low-temperature endothermic effect can be produced from clay minerals if the weight of a sample component that is undergoing a low-temperature endothermic reaction becomes so low that the thermal effects from all parts of the sample do not even out at the thermocouple junction. Under such conditions, as the furnace temperature is raised the upper part of the sample dehydrates first, and this dehydration proceeds to completion before the sample in the lower part of the sample holder reaches the dehydration temperature. The differential thermocouple which has its bead and all its length common to the two halves of the sample thus tends to record two separate dehydration reactions. This is not the case when the differential thermocouple is arranged along the axis of the sample holder, for although the sample dehydrates as before, the arrangement of the thermocouple is such that the thermocouple records very little of the thermal reactions that take place in the upper half of the sample, its bead alone being in contact with this part of the sample. These observations imply that conduction of heat along the thermocouple wires is an important means of transferring the heat of reaction from the sample to the thermocouple bead. They also indicate that most of the thermal effect comes from the sample in the immediate vicinity of the thermocouple wires. These observations do not appear to have been considered in the theory of differential thermal analysis as yet, though the transfer of heat from the sample holder to sample (or vice versa) by conduction along the thermocouple wires, which results in a reduced peak area, has been discussed by Sewell (1955), Boersma (1955) and de Josselin de Jong (1957) for simplified geometrical arrangements. The observation that the upper half of the sample is largely wasted when the thermocouple is arranged vertically is in agreement with de Josselin de Jong's conclusion that "if the sample height surpasses a certain limit, the surplus of material does not influence the peak area, apparently being out of the influence zone of the thermocouple."

When the differential thermocouple is arranged radially across the

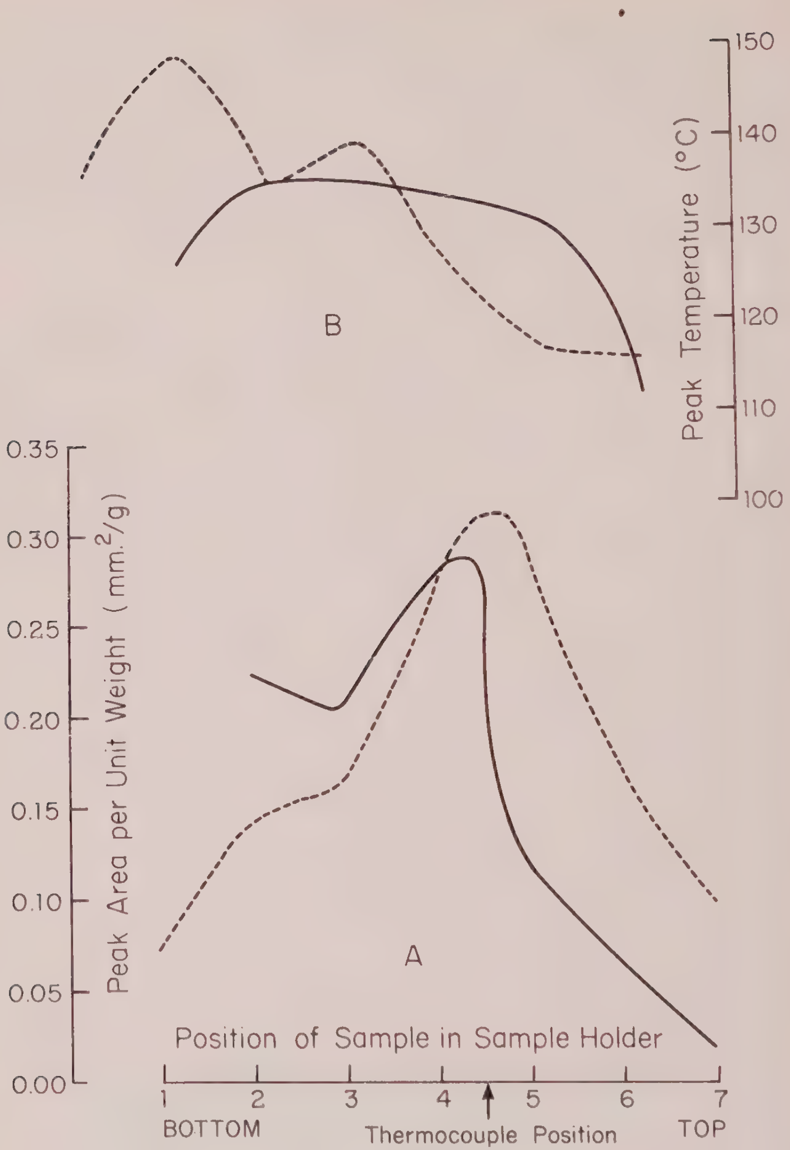

FIG. 4. Effect of the position of the sample in the sample holder on peak area (A) and peak temperature (B).

- - - - Differential thermocouple arranged radially through the center of the cylindrical sample holder as in Fig. 1A.

— — Differential thermocouple arranged along the axis of the cylindrical sample holder as in Fig. 1B.

center of a *covered* sample holder no extra low-temperature endothermic peak is introduced in the differential thermal curves of diluted samples of clay minerals, for the thermal effects from all parts of the sample reach the thermocouple junction at nearly the same time. The effect of the covering lid is to trap water vapor beneath it in the upper layers of the sample, so that a pressure of water vapor is generated which raises the dehydration temperature of the upper layers to a value which approaches that for the lower layers.

However, the fact that the effects described here have, for natural clay samples, been observed only with vermiculite indicates that it also must play a role. In the structure of this mineral the silicate layers are separated by the exchangeable cations which surround themselves by either a single or double sheet of water molecules, depending upon the relative humidity and temperature of the surrounding air (Walker and Cole 1957). Should water vapor concentrate within a sample of vermiculite it will be absorbed so as either to expand the structure from one possessing a single sheet to one possessing a double sheet of water molecules, or to increase the number of water molecules in the double sheet structure. When the differential thermocouple is arranged radially across the center of an uncovered sample holder, water vapor moves upwards to the atmosphere and downwards into the sample as the top layers dehydrate. That moving downwards cannot readily escape from the bottom half of the sample holder and produces a broad double endothermic peak (vermiculite sample A, Fig. 3) typical of a well-filled double layer structure. The peak from the upper half of the sample is much sharper and is typical of a partially-filled double layer or a single layer structure. When the differential thermocouple is arranged along the axis of the sample holder a sharp peak is produced from both halves of the sample since water vapor can readily escape from both regions. When the sample is covered by a lid the egress of water vapor is restricted to the thermocouple lead-ins, so that more uniform conditions are created within the sample holder and both top and bottom halves of the sample dehydrate under similar conditions and at similar temperatures. A true differential thermal record is then produced for vermiculite (and for montmorillonite too since it has a similar structure) with both types of differential thermocouple arrangements. Other examples of the importance of a lid in modifying differential thermal curves have been discussed by Kulp, Wright and Holmes (1949) for rhodochrosite and by Rowland and Jonas (1949) for siderite.

It should be noted that despite the limitations discussed here, which apply only to the low-temperature region, the radial arrangement of the differential thermocouple makes more economical use of the sample than the axially arranged one and should possess a higher sensitivity despite there being high conduction losses to the inert sample because of the short length of connecting wire used. The arrangement also has the advantage that the thermocouple beads can be more easily centered and this enables a better control of base-line drift. It becomes particularly valuable when small weights of sample only are available for the sample can (and should) be sandwich packed around the differential thermocouple leads so as to produce a maximum, but true, differential thermal effect.

REFERENCES

BOERSMA, S. L. (1955).—A theory of differential thermal analysis and new methods of measurement and interpretation. *J. Amer. Ceram. Soc.*, **38,** 281–284.

CARTHEW, A. R., AND COLE, W. F. (1953).—An apparatus for differential thermal analysis, *Aust. J. Instrum. Tech.*, **9,** 23–30.

COLE, W. F., AND HOSKING, J. S. (1957).—Clay mineral mixtures and interstratified minerals; Chap. X, pp. 248–274, in "Differential Thermal Investigation of Clays," Mineralogical Society, London.

DE JOSSELIN DE JONG, G. (1957).—Verification of use of peak area for quantitative differential thermal analysis, *J. Amer. Ceram. Soc.*, **40,** 42–49.

KULP, J. L., WRIGHT, H. D., AND HOLMES, R. J. (1949).—Thermal study of rhodochrosite, *Am. Mineral.*, **34,** 195–219.

MACKENZIE, R. C., AND MITCHELL, B. D. (1957).—Apparatus and technique for differential thermal analysis; Ch. II, pp. 23–64, in "Differential Thermal Investigation of Clays," Mineralogical Society, London.

MIELENZ, R. C., SCHIELTZ, W. C., AND KING, M. E. (1954). Thermo-gravimetric analysis of clay and clay-like minerals; pp. 285–314, in "Second National Conference on Clays and Clay Minerals," Columbia, Missouri, National Academy of Sciences—National Research Council Publication 327.

ROWLAND, R. A., AND JONAS, E. C. (1949).—Variations in differential thermal analysis curves of siderite, *Am. Mineral.*, **34,** 550–558.

SEWELL, E. C. (1955). The effect of heat conduction along thermo-couple wires on peak areas in differential thermal analysis, *Research Note*, Building Research Station, D.S.I.R.

WALKER, G., AND COLE, W. F. (1957).—The vermiculite minerals; Ch. VII, pp. 191–206, in "Differential Thermal Investigation of Clays," Mineralogical Society, London.

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SOME FACTORS CONCERNING THE NATURE AND ORIGIN OF GLAUCONITE

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ABSTRACT

The compositional variations of glauconite can be related to differences in mixed-layering involving "illite" (10 Å) and "montmorillonite" (expandable) layers. The interlayer cations potassium and rubidium and the octahedral cation iron decrease with increasing amounts of expandable layers. Strontium increases rapidly with increasing per cent expandable layers and because it is largely exchangeable is assumed to be present in the expandable layers as an exchange ion.

The relationships between structure and composition are used to examine Burst's model for glauconitization. Pellets that occur in clean sandstones, limestones and dolomites are almost exclusively monomineralic, consisting only of mixed-layer illite/montmorillonite with a low per cent expandable layers. Pellets that occur in argillaceous sandstones and marls frequently contain extraneous clay minerals and the illite/montmorillonite contains a high per cent expandable layers. Because of the well known observation that glauconite forms only at relatively low sedimentation rates it is concluded that the pellets occurring in argillaceous sandstones and marls represent less glauconitized material than those pellets occurring in clean sandstones, limestones, and dolomites. These observations fit Burst's model for glauconitization which assumes a degraded 2:1 layer-lattice structure as the parent material and the glauconitization process as a gradual substitution of iron for aluminum in the octahedral positions, a concomitant gradual increase in lattice charge (arising from the octahedral layer) and a consequent increase in interlayer potassium which results in the collapse of increasingly more layers to the non-expandable 10 Å type. It is also shown that potassium increases with octahedral charge and is independent of tetrahedral charge, a phenomenon predictable from Burst's model but no other.

Glauconites differ significantly in composition and structure with geologic age. Young glauconites are lower in potassium (and thus higher in per cent expandable layers) and are more frequently mineralogically heterogeneous than older glauconites. A large part of these age differences appears to be explainable on the basis of lithologic association. However, there is some evidence for late epigenetic gain of potassium.

Weaver has shown similar differences with geologic age in the clay mineral assemblages of shales. Because of this similarity and because a good case can be made for attributing most of the variations in the mineralogy of glauconite pellets to diagenetic effects, it is suggested that diagenesis may have played an important role in the formation of the clay mineral assemblages of shales.

INTRODUCTION

Burst (1958*a*, 1958*b*) has recently shown that glauconite pellets are composed of mineralogically heterogeneous material. He has divided the pellets into four classes on the basis of *x*-ray diffraction data: (1) Ordered 10 Å structures, (2) Disordered 10 Å structures, (3) Interlayered structures, and (4) Mixed mineral pellets. The first three classes form a series of increasing potassium from class (3) to class (1). The fourth class includes glauconite pellets composed of more than one clay mineral. No relation was found between external morphology and mineralogical composition. Burst has shown clearly that since some pellets are mineral mixtures any interpretation of the chemical composition of glauconite must be aided by an *x*-ray diffraction determination of the mineralogical composition.

Investigations into the origin of glauconite previous to those of Burst were greatly handicapped by the lack of *x*-ray diffraction data. One of the major problems concerning the origin of glauconite has been the type of starting (parent) material. The conclusions of these previous investigations as to the nature of the glauconitization process have been colored by what appeared to be the parent material in a particular instance of glauconite formation. For this reason Galliher (1935, 1939) proposed that glauconitization involved the alteration of biotite, the chemical changes involved being: (1) oxidation of the iron already present, (2) partial loss of potassium, (3) "hydration," and (4) partial loss of aluminum. Takahashi (1929, 1939), on the other hand suggested that the parent material for glauconite formation was an amorphous gel of aluminates and silicates. This material, he assumed, was derived from a number of preexisting materials such as volcanic glass, mica, clays in fecal pellets, feldspar, etc., by hydration and consequent gelatinization. Subsequent recrystallization during diagenesis ("submarine metamorphism") along with compositional changes give rise to glauconite. The composition changes that Takahashi proposed include an increase in potassium and iron and a decrease in aluminum.

The model of glauconitization proposed by Burst assumes that the immediate starting material in the formation of glauconite can be any degraded (expandable) layer lattice mineral. The process of glauconitization according to this model consists of absorption of potassium and iron by the degraded layer lattice material under the proper environmental conditions. This model fits the known data on glauconites better than any previously proposed. The main purpose of the present study was to attempt to test the model for glauconitization with data supplementary to that provided by Burst. An additional purpose was to relate the compositional and structural variations in glauconite that are of interest to the use of this material in the radioactive dating of sedimentary rocks.

EXPERIMENTAL METHODS

X-ray Diffraction Determinations

Oriented specimens of the glauconites were prepared for the *x*-ray diffraction determinations. A sample was first disaggregated in distilled water, either by grinding or ultrasonics, and the suspension was then centrifuged through a porous porcelain plate. This technique was devised by Kinter and Diamond (1956).

The type and extent of interlayering was determined from diffraction patterns of treated samples. Patterns were obtained on untreated, glycol solvated, and potassium-treated (with a 1N KCl solution) samples. Most of the samples were also run after heat treatments in the range 500–600° C. for a period of $\frac{1}{2}$ hour in order to detect the presence of chlorite layers. The per cent expandable layers was determined from the position of the combined 001/001 reflection following glycol solvation and also following potassium treatment. The per cent expandable layers was read from the curves of Brown and MacEwan (1951) and Weaver (1956) relating *d*-spacing to amount and type of interlayering, and is reported to the nearest five per cent.

Randomly oriented *x*-ray diffraction patterns were run on a number of glauconites to determine polymorphic type.

Chemical Analyses

Potassium was determined flame photometrically with a Perkin-Elmer instrument using lithium as the internal standard. The samples were taken into solution using a HF-$HClO_4$ attack. The standard deviation of the determinations is ± three per cent of the amount present.

Strontium and rubidium were determined *x*-ray spectrographically using the method described by Hower (1959). Standards were prepared by mixing carbonates of Rb and Sr with Al_2O_3. Arsenic was used as the internal standard. The precision of trace element *x*-ray spectrographic techniques is best expressed in terms of absolute amount. The standard deviation of the Sr and Rb determinations is about ±5 ppm. Therefore, the relative precision of the determination of Sr in some glauconites is quite poor.

Iron was determined for a few samples by a semi-quantitative *x*-ray spectrographic method. A one point working curve was constructed using an analyzed sample (the Bashi fm.) as the known point. The slope of the working curve was adjusted by calculating absorption coefficients for six additional analyzed glauconites relative to the Bashi sample. The standard deviation of the determinations is ±2 per cent of the amount present. The accuracy is thought to be within ±10 per cent. Iron is reported as Fe_2O_3.

RESULTS AND DISCUSSION

Relationship Between Glauconite Composition and Structure

As discussed in the previous section, the method of sample preparation for *x*-ray diffraction determinations was different from that employed by Burst (1958*a*, 1958*b*). The more vigorous orientation technique results in a lack of patterns showing the 448 Å peak exhibited by

Burst's "disordered" type of glauconite. A comparison of the results of both methods can be briefly made as follows. All glauconites are interlayered to a certain extent. The interlayering is almost exclusively between expandable (montmorillonitic) layers and non-expandable 10 Å layers. Patterns obtained from glycolated, potassium-treated, and heat-treated samples show no appreciable amount of chlorite or vermiculite layers in any glauconite. Burst (personal communication, 1960) has detected chlorite in some glauconites and has pointed out that the heat treatment used in this study would destroy some sedimentary chlorites. Glauconites exhibit a continuous series from <5 per cent to approximately 40 per cent expandable layers. A comparison with Burst's first three classes can be related to the amount of expandable layers. An approximate comparison is that "ordered" glauconites contain ≤ 10 per cent expandable layers, "disordered" glauconites 10–20 per cent expandable layers, and "interlayered" glauconites ≥ 20 per cent expandable layers. Figure 1 shows the diffraction patterns of glauconites that cover the range from <5 per cent to approximately 30 per cent expandable layers.

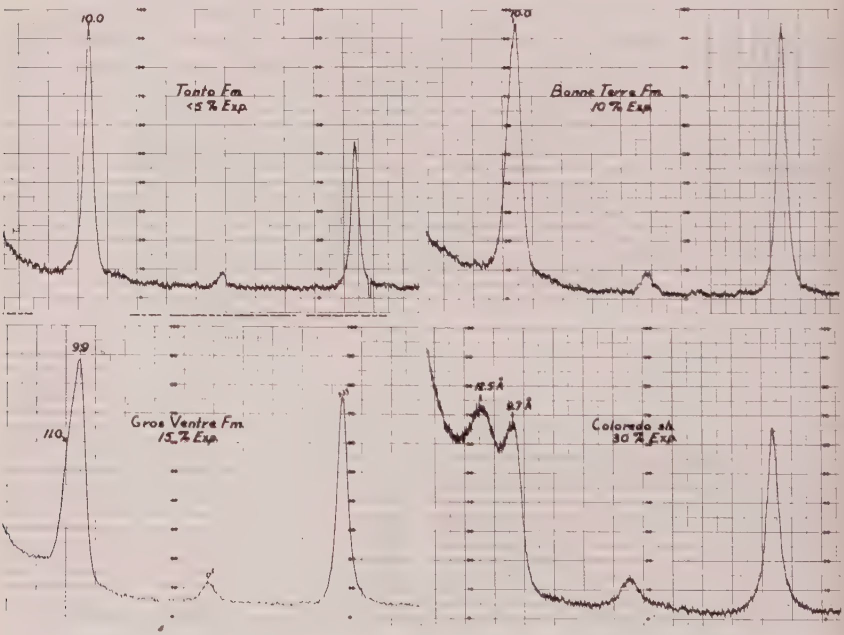

FIG. 1. Examples of monomineralic glauconite pellets composed of mixed-layer illite/montmorillonite. The samples are glycol solvated. (upper left) Tonto Fm., Cambrian, 5% expandable layers, 6.7% K; (upper right) Bonne Terre Fm., Cambrian, 10% expandable layers, 6.9% K; (lower left) Gros Ventre Fm., Cambrian, 15% expandable layers; (lower right) Colorado shale, Cretaceous, 25% expandable layers, 4.2% K.

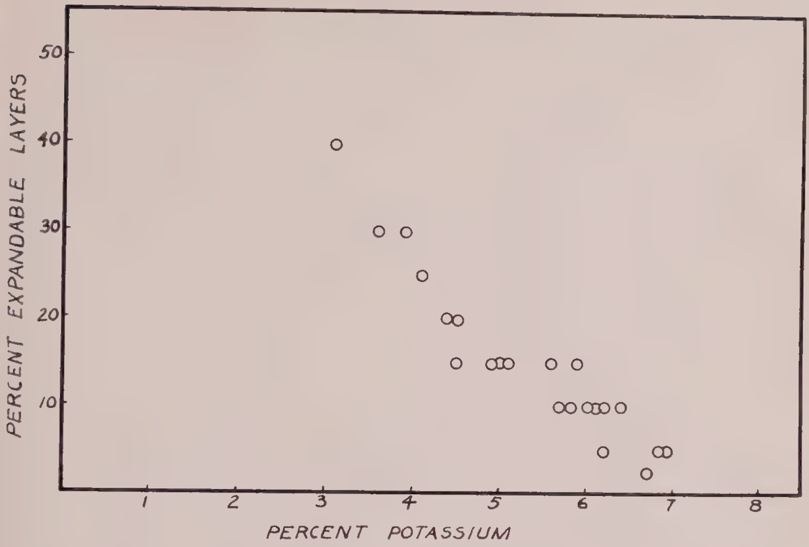

FIG. 2. The relationship between weight per cent potassium and per cent expandable layers in monomineralllic mixed-layered illite/montmorillonite glauconite pellets.

Randomly oriented diffraction patterns gave the same results as those reported by Burst (1958*b*). Glauconites with a low per cent of expandable layers are the 1*M* polymorph; glauconites with a high per cent of expandable layers are the 1*Md* polymorph.

Table I is a summary of the structural and some of the compositional data on glauconites for which *x*-ray diffraction data are available. A portion of the diffraction data was obtained during the present study. The remaining diffraction data were obtained from Burst (1958*a*, 1958*b*) and Warshaw (1957). The sources for data of all types are noted in the table. The values reported of per cent expandable layers from the Burst sources were roughly estimated from his patterns of untreated samples. None of these estimated values are used in the plots relating compositional and structural changes which follow.

The samples are listed in Table I in order of increasing amounts of expandable layers. Some relationships between structure and chemical composition can be noted. Potassium decreases with increasing per cent expandable layers. This is the same trend noted by Burst for his first three classes. Figure 2 is a plot of weight per cent potassium against per cent expandable layers for glauconites that are not clay mineral mixtures. The plot indicates a continuous series in glauconites that covers a wide range of potassium content.

Other elemental variations can be related, at least in part, to structural variations. Figure 3 is a plot of strontium against per cent expand-

TABLE I. SUMMARY OF GLAUCONITE STRUCTURAL AND COMPOSITIONAL DATA

Sample	Age	Lithology	Per cent Expandable	Burst Class	Mixed Mineral	Per cent K	ppm Rb	ppm Sr	Per cent Fe_2O_3	Sample No.
Tonto Fm.	Cambrian	clean ss	5 (1)	—	none	6.7 (1)	300	10 (1)	19.4 (1)	1
Birkmose Mem. (Franconia Fm.)	Cambrian	clean ss	5 (1)	—	none	6.9 (1)	290	20 (1)	24.9 (1)	2
Bonne Terre Fm.	Cambrian	dolomite	5 (1)	Ordered	none	6.9 (2)	—	— —	22.9 (2)	3
Stenbrottet ls.	Ordovician	limestone	5 (1)	—	none	6.2 (4)	307	13 (4)	— —	4
Ceratopyge ss	Ordovician	? ss	10 (5)	Ordered	none	6.0 (2)	—	— —	15.1 (2)	5
Reno Mem. (Franconia Fm.)	Cambrian	clean ss	10 (1)	Ordered	none	6.4 (1)	265	15 (1)	21.5 (1)	6
Mt. Whyte Fm.	Cambrian	calc. ss	10 (1)	—	none	— —	180	116 (4) (calcite)	— —	7
Tyner Fm.	Ordovician	limestone	10 (3)	—	—	— —	—	— —	— —	8
Vidono Fm.	Cretaceous	chert	10 (3)	—	—	5.7 (3)	—	— —	18.7 (3)	9
H & S #1	Cret./Tert.	—	10 (3)	—	—	6.2 (3)	—	— —	17.2 (6)	10
Mahele Fm.	Paleocene	clean ss	10 (3)	—	—	— —	—	— —	— —	11
Bashi Fm.	Eocene	marl	10 (1)	Disordered	none	5.8 (1)	290	40 (1)	22.7 (2)	12
San Saba Mem. (Wilberns Fm.)	Cambrian	limestone	10 (1)	—	none	6.1 (4)	244	10 (4)	—	13
Gros Ventre Fm.	Cambrian	arg. ss	15 (1)	—	kaolinite	— —	275	25 (1)	— —	14
Riley Fm.	Cambrian	? xx	15 (1)	—	none	5.6 (4)	—	— —	— —	15
Murray sh	Cambrian	arg. ss	15 (1)		none	5.9 (4)	171	28 (4)	— —	16
Carlisle Cent. Fm.	Devonian	arg. silt	15 (1)		none	4.9 (4)	309	39 (4)	-	17
Navesink Fm.	Cretaceous	marl	15 (1)	Ordered	none	5.1 (1)			22.3 (1)	18
Warshaw #8	Cretaceous	? ss	15 (3)	—	—	— —	—	— —	— —	19
Temblador Fm.	Cretaceous	arg. ss	15 (3)	—	—	— —	—	— —	— —	20
H & S #4	Cret./Tert.	—	15 (3)	—	—	5.0 (3)	—	— —	24.8 (6)	21
H & S #4	Cret./Tert.	—	15 (3)	—	—	5.0 (3)	—	— —	24.9 (6)	22
Warshaw #9	Cretaceous	ark. ss	15 (3)			4.5 (3)	—	— —	20.6 (6)	23
Pierson Fm.	Eocene	—	15 (5)	Disordered	none	5.1 (2)	—	— —	19.3 (2)	24
Wilcox Fm.	Eocene	marl	10–20 (5)	Mixed Mineral	—	— —	—	— —	— —	25

TABLE I (*continued*)

Sample	Age	Lithology	Per cent Expandable	Burst Class	Mixed Mineral	Per cent K	ppm Rb	ppm Sr	Per cent Fe_2O_3	Sample No.
Gatchell Fm.	Eocene	?	10–20 (5)	Mixed Mineral	—	— —	—	— —	— —	26
Martinez Fm.	Paleocene	ark. ss	20 (3)	—	—	4.5 (3)	—	— —	22.5 (3)	27
Morrow Fm.	Pennsylv.	sandy sh.	20 (5)	Mixed Mineral	—	— —	—	— —	— —	28
Burditt marl	Cretaceous	marl	20 (5)	Disordered	none	5.3 (2)	—	— —	16.9 (2)	29
"Subsurface"	Eocene	?	20 (5)	Disordered	none	4.0 (2)	—	— —	14.1 (2)	30
H., New Jersey	?	?	20 (1)	—	none	4.4 (1)	—	— —	— —	31
Matalani Fm.	Eocene	chert	20 (3)	—	—	— —	—	— —	— —	32
Domengine Fm.	Eocene	arg. ark ss	20 (3)	—	—	— —	—	— —	— —	33
Colorado sh.	Cretaceous	arg. ss	25 (1)	—	none	4.2 (1)	320	100 (1)	9.4 (1)	34
Carrizo Fm.	Eocene	marl?	25 (1)	Interlayered	none	— —	—	— —	— —	35
Panoche Fm.	Cretaceous	arg. ss	20–30 (5)	Interlayered	none	— —	—	— —	— —	36
Eutaw Fm.	Cretaceous	—	20–30 (5)	Interlayered	none	— —	—	— —	— —	37
Ripley Fm.	Cretaceous	calc. arg ss	20–30 (5)	Interlayered	none	— —	—	— —	— —	38
Prairie Bluff Fm.	Cretaceous	marl	20–30 (5)	Mixed Mineral	—	— —	—	— —	— —	39
Lodo Fm.	Paleocene	?	20–30 (5)	Interlayered	none	— —	—	— —	— —	40
Reklaw Fm.	Eocene	arg. ss	20–30 (5)	Mixed Mineral	—	— —	—	— —	— —	41
Sundance Fm.	Jurassic	arg. ss	30 (1)	—	kaolinite	3.9 (1)	240	115 (1)	8.9 (1)	42
Moody's Branch Fm.	Eocene	marl	30 (1)	—	none	3.6 (1)	150	170 (1)	14.2 (1)	43
Winona Fm.	Eocene	arg. ss	30 (5)	Interlayered	none	— —	—	— —	— —	44
Mathews Ldg.	Paleocene	marl	30–40 (5)	Interlayered	none	— —	—	— —	— —	45
Weches Fm.	Eocene	arg. ss	30–40 (5)	Mixed Mineral	—	— —	—	— —	— —	46
Byram Fm.	Oligocene	marl	40 (1)	Interlayered	none	3.1 (1)	165	245 (1)	— —	47

(1) This investigation.
(2) Burst (1958b).
(3) Warshaw (1957).
(4) Hurley, P. M., Fairbairn, H. W., Pinson, W. H., and Winchester, J. (1958), Age study of Lower Paleozoic glauconites: Sixth Annual Progress Report, USAEC Contract AT (30-1)-1381, pp. 53–62.
(5) Burst (1958a).

able layers for glauconites which are not clay mineral mixtures and contain no detectable calcite. The strong positive correlation suggests that Sr is an exchange ion present in the expandable layers. Table II compares the Sr contents of glauconites that have been treated with a one normal NH_4Ac solution with untreated samples. It is apparent that most of the Sr in these glauconites is easily exchangeable. The conclusion is that most of the Sr present in glauconite pellets is indigenous to the glauconite and is adsorbed on the basal plane surfaces of the expandable layers. This conclusion differs from that of Herzog et al (1958), who determined Sr in glauconites in the course of Sr Rb dating studies, and attributed the strontium variations in glauconite wholly to calcite contamination. Their HCl treatment to remove calcite would also remove exchangeable Sr held by the glauconite. However, addition of "common" Sr to glauconite samples by calcite contamination could undoubtedly be significant for glauconites that are intrinsically very low in Sr. An example is sample number 8 in Table I (Mt. Whyte Fm.) which contains only 10 per cent expandable layers and 116 ppm. Sr. Calcite is readily detectable in this sample by x-ray diffraction.

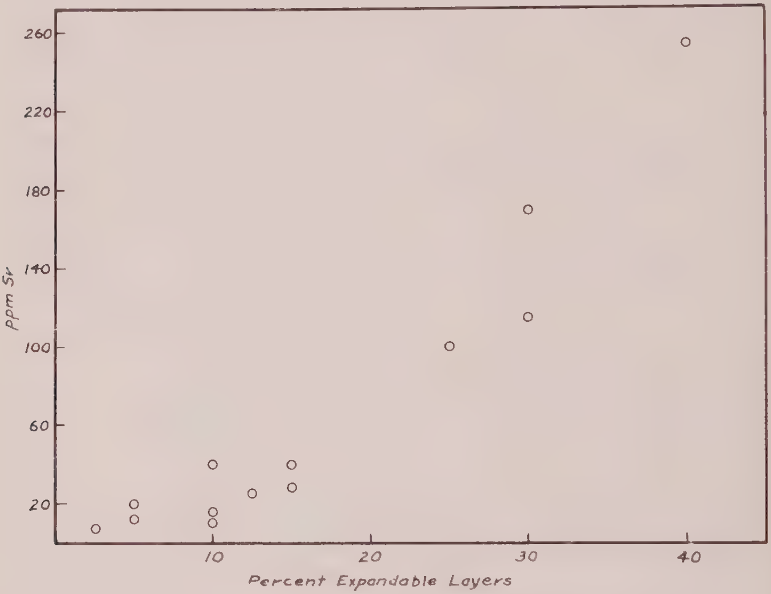

FIG. 3. The relationship between strontium and per cent expandable layers in carbonate-free glauconite pellets.

Rubidium decreases roughly with increasing amounts of expandable layers (Fig. 4). Rubidium does not decrease as rapidly as potassium,

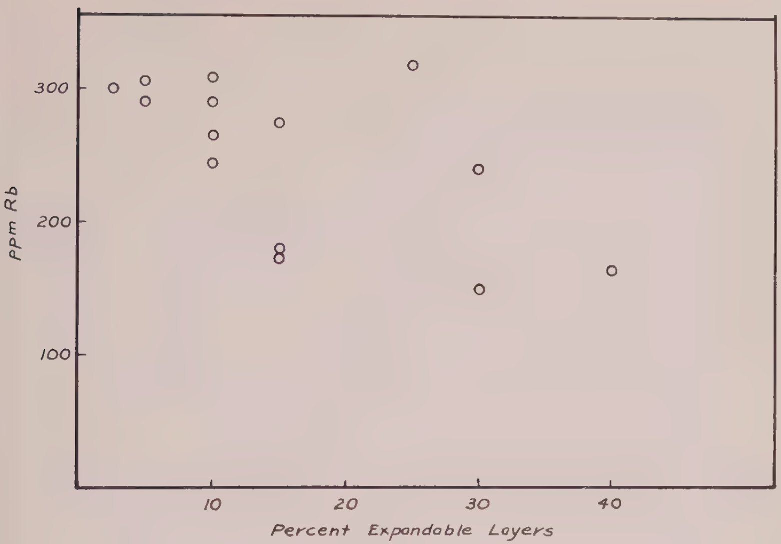

FIG. 4. The relationship between rubidium and per cent expandable layers in glauconite pellets.

robably because it is preferentially adsorbed in the expandable layers. n the basis of the most limited data shown in Table II, the Rb is non-xchangeable. Most of the Rb is undoubtedly held in the non-expandable ayers.

Potassium, rubidium, and strontium are interlayer cations in glau-onite and would thus be expected to show some relationship with the er cent expandable layers. Iron is octahedrally coordinated in the

ABLE II. EFFECT OF NH_4Ac TREATMENT ON THE STRONTIUM CONTENT OF GLAUCONITES

Sample	% Expand-able	Sr		Rb	
		Untreated	NH_4 treated	Untreated	NH_4 treated
Tonto Fm.	< 5	~ 10	~10	310	295
Birkmose Fm.	5	20	~10	290	—
Bashi Fm.	10	40	~10	290	—
Franconia Fm.	10	~ 15	~10	265	265
Gros Ventre Fm.	15	25	~10	275	—
Colorado Fm.	25	100	25	320	330
Sundance Fm.	30	115	40	245	235
Moody's Branch Fm.	30	170	60	145	150
Byram Fm.	40	245	25	165	175

glauconite structure and would therefore not necessarily show any relation with the nature of inter-layering. Figure 5 is a plot of total iron, reported as Fe_2O_3, against per cent expandable layers. There appears to be a rough correlation, the possible significance of which will be discussed in a later section.

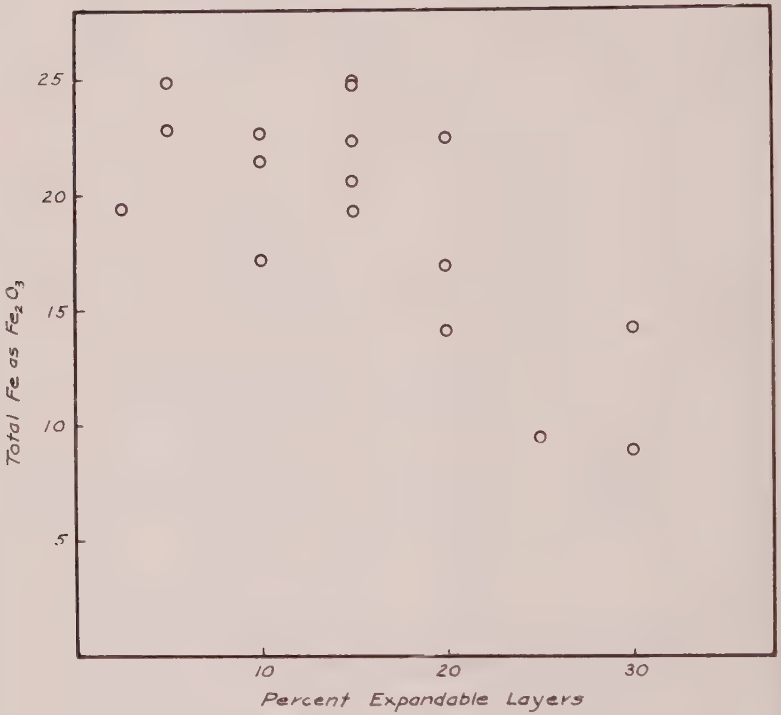

FIG. 5. The relationship between total iron as Fe_2O_3 and per cent expandable layers in glauconite pellets.

RELATION BETWEEN LITHOLOGIC TYPE OF ENCLOSING SEDIMENT AND GLAUCONITE STRUCTURE

Warshaw (1957) has pointed out a relationship between glauconite structure and the lithologic nature of the rock type in which the pellets occur. For twelve occurrences she found the following relationships: Glauconites equivalent to Burst's "ordered" and, in part, "disordered" type occurred in a dolomite, a chert, and sandstones in which the detrital grains are mostly quartz, quartzite, or chert and the cement is silica and/or carbonates; glauconites of Burst's "disordered" type occurred in a subarkosic sandstone and a bentonitic shale; "mixed-layer" type glauconites occurred in sandstones containing large amounts of feldspar, clay minerals other than glauconite, and mica.

Included in Table I is, when known, the general nature of the lithologic type of the enclosing sediment in which the glauconite sample occurs. The lithologic description is generalized and simplified—it is hoped not oversimplified. Table III is a summary of these data, dividing glauconites into two groups, those with ≤10 per cent expandable layers and those with ≥15 per cent expandable layers. Glauconites with ≤10 per cent expandable layers occur predominantly in non-argillaceous quartzose sandstones and "normal" carbonate rocks (limestones and dolomites). Glauconites with ≥15 per cent expandable layers occur predominantly in argillaceous sandstones and marls.

The Origin of Glauconite

Burst (1958*a*, 1958*b*) has proposed, on the basis of his investigations, a model for the origin of glauconite that reconciles many of the older proposals. He suggests that the process of glauconitization requires simply (1) a degraded silicate layer lattice, (2) a plentiful supply of iron and potassium, and (3) a suitable redox potential. The redox potential is frequently supplied by a locally reducing environment associated with decaying organic matter, in a generally oxidizing environment. The locally reducing environment can be present in fecal pellets, inside foraminiferal tests, etc., hence the frequent glauconitization of these materials. Other factors, such as sedimentation rate, water temperature, water depth and parent material can have an influence on the specific nature (type) of glauconite that forms. Burst further suggests that the chemical changes involved in glauconitization are "the adjustment by absorbing iron and potassium into . . . impoverished clay lattices in amounts controlled, in part, by the surrounding sea-water chemisry. . . . " By impoverished is meant degraded; that is, a layer-lattice tructure consisting largely or wholly of loosely bonded (expandable) ayers. This expandable material could also include the montmorillonoids as well as degraded originally non-expandable layer-lattices. Preumably, given the proper chemical conditions and enough time the maerial would approach the composition and structure of Burst's "mineral glauconite." Burst has defined the "mineral glauconite" on the basis of his "ordered" glauconites—those which have few expandable layers, ordered stacking, and are high in potassium.

The data reported in previous sections can be profitably used to test he model for glauconitization proposed by Burst. First, however, it would be well to attempt to describe the mechanism of chemical change n more detail. The "absorption of potassium and iron" would involve

Table III. Relation Between Glauconite Structure and Lithologic Type of Enclosing Sediment

Sample	Age	Lithology
a. Glauconites with ≤10 per cent expandable layers		
Tonto Fm.	Cambrian	clean quartzose ss
Birkmose Mem.	Cambrian	clean quartzose ss
Reno Mem.	Cambrian	clean quartzose ss
Park Fm.	Cambrian	clean quartzose ss
Mahele Fm.	Paleocene	clean quartzose ss
Mt. Whyte Fm.	Cambrian	calcareous ss
Stenbrottet ls.	Ordovician	limestone
San Saba Mem.	Cambrian	limestone
Tyner Fm.	Ordovician	dolomite
Bonne Terre Fm.	Cambrian	dolomite
Vidono Fm.	Cretaceous	chert
Bashi Fm.	Eocene	marl
b. Glauconites with ≥15 percent expandable layers		
Lion Mt. Mem.	Cambrian	limestone
Gros Ventre Fm.	Cambrian	argillaceous ss
Murray sh.	Cambrian	argillaceous ss
Carlisle Cent. Fm.	Devonian	argillaceous silt
Temblador Fm.	Cretaceous	argillaceous ss
Warshaw #9	Cretaceous	argillaceous felds. ss
Domengine Fm.	Eocene	argillaceous felds. ss
Colorado Fm.	Cretaceous	argillaceous ss
Panoche Fm.	Cretacoeus	argillaceous ss
Ripley Fm.	Cretaceous	calc. argillaceous ss
Reklaw Fm.	Eocene	argillaceous ss
Sundance Fm.	Jurassic	argillaceous ss
Winona Fm.	Eocene	argillaceous ss
Weches Fm.	Eocene	argillaceous ss
Navesink Fm.	Cretaceous	marl
Wilcox Fm.	Eocene	marl
Burditt Marl	Cretaceous	marl
Carrizo Fm.	Eocene	marl
Prairie Bluff Fm.	Cretaceous	marl
Moody's Branch Fm.	Eocene	marl
Mathews Ldg.	Paleocene	marl
Byram Fm.	Oligocene	marl
Martinez Fm.	Paleocene	felds. ss
Morrow Fm.	Pennsylvanian	arenaceous sh.
Matalani Fm.	Eocene	chert

he adsorption and subsequent fixation of these ions in the lattice and the imultaneous release of other ions that were either exchanged on or fixed in the lattice of the parent material. During the glauconitization process iron would have to make its way into the octahedral layer of the parent layer lattice mineral, where it would commonly take the place of aluminum. The replacement mechanism would most easily be accomplished in parent material of a degraded nature consisting largely of expandable layers—the parent material suggested by Burst. The iron ions would migrate into the expandable layers, be adsorbed there, and eventually diffuse into the octahedral layer, replacing aluminum ions. Most kely the rate of supply of iron ions would not be high considering the ow concentration of soluble iron compounds in the ocean. Also, the replacement process would probably be slow. Once the material being lauconitized was buried very far below the sediment-sea water interface (where the proper chemical environment is present) the process would stop.

A few observations can now be made relating this proposed mechanism f glauconitization to the known facts of glauconite formation.

A low or negative sedimentation rate has been recognized as a condition necessary for the formation of glauconite (Cloud, 1955). If the rate f sedimentation is too high, glauconite does not form. In terms of the proposed model this means that the rate of supply of degraded argillaceous material must be low and that the material being glauconitized would remain at the sediment-sea water interface a long time. There would, of course, be a range of sedimentation rates—other factors being constant—over which glauconite could form. The glauconitization process would not proceed as far when the sedimentation rate was at the high end of the range as toward the lower. Therefore, the glauconitization process under more rapid sedimentation would be arrested somewhere along the series "degraded layer lattice mineral"–"mineral glauconite." This is here proposed as the reason for the relationship between glauconite structure and lithologic type of the enclosing sediment hown in Table III. Glauconites containing ≥ 15 per cent expandable ayers are found dominantly in argillaceous sandstones and marls in which the rate of supply of argillaceous material is high. In contrast, lauconites with ≤ 10 per cent expandable layers occur dominantly in ean quartzose sandstones and normal carbonate rocks in which the rate of supply of argillaceous material is low.

Burst (1958*b*) has shown a similar effect of sedimentation rate on the lauconite type that forms. In a group of glauconites he has studied from he Tertiary, glauconites occurring at unconformities approach his "ordered" type in contrast to glauconites occurring in conformable sediments that tend to be of his "disordered" and "interlayered" types. Presumably the glauconites occurring at unconformities had a longer tim to approach the ordered potassium-rich (low per cent expandable layers end product and remained near the sediment-sea water interface longer

Since the rate of formation of glauconite is slow, it can be conclude that degraded or expandable material with a high lattice charge woul probably not be easily glauconitized. Weaver (1958*c*) has shown tha such material rapidly adsorbs potassium from sea water and collapses to non-expandable lattice. Once the layers collapse it would be difficult fo iron to make its way into the octahedral layers and glauconitizatio would proceed only slowly, if at all. Therefore, if the parent material fo glauconite formation is a degraded layer lattice mineral, its susceptibilit to glauconitization should be greatly enhanced if the lattice charge wer relatively low. This means, then, an increase in net lattice charge an therefore a consequent increase in the number of interlayer cation (mainly potassium) as glauconitization proceeds. This fits the model suggested by Burst. If this model is at least approximately correct, potassium and iron should be directly proportional to each other and both should be inversely proportional to the per cent expandable layers. The model, however, does not require a one to one correlation between th parameters. It means only that potassium (which depends on net lattice charge) and iron increase—though not necessarily at the same rate— together during glauconitization. Figure 5, presented previously without a suggested explanation, shows that iron is roughly inversely proportional to per cent expandable layers. Figure 6 shows that iron is proportional to potassium. These relationships conform with the predictions made above and based on Burst's model for glauconitization. These relationships would not be predicted by other proposed mechanisms of glauconitization such as crystallization from amorphous material or the alteration of biotite.

Another question which arises is that of the structural position of the increase in net lattice charge during glauconitization. Again following the proposed model, one would conclude that the increase in charge takes place in the octahedral layer—for it is in this layer that extensive ionic substitution takes place. It is also possible, of course, that some substitution takes place in the tetrahedral layer—of iron for aluminum or silicon—as suggested by Hoebeke and Dekeyser (1955). However, the presence of iron in tetrahedral coordination has yet to be proved (Warshaw, 1957). Assuming that the increase in net charge takes place by substitutions in the octahedral layer, it can be predicted that the total number of interlayer cations would increase with the net octahedral charge and that no specific relationship would be expected between the umber of interlayer cations and the net tetrahedral charge. Figures 7 nd 8 indicate a confirmation of this prediction. Figure 7 shows an in-rease in potassium with increasing octahedral charge. Figure 8 shows no bvious relationship between potassium and tetrahedral charge. The ata plotted in these figures were obtained from structural formulas cal-ulated by Hendricks and Ross (1941), Burst (1958*b*) and Warshaw 1957). The relationships are somewhat open to question for they may result, in part, from the method of calculation of a structural formula.

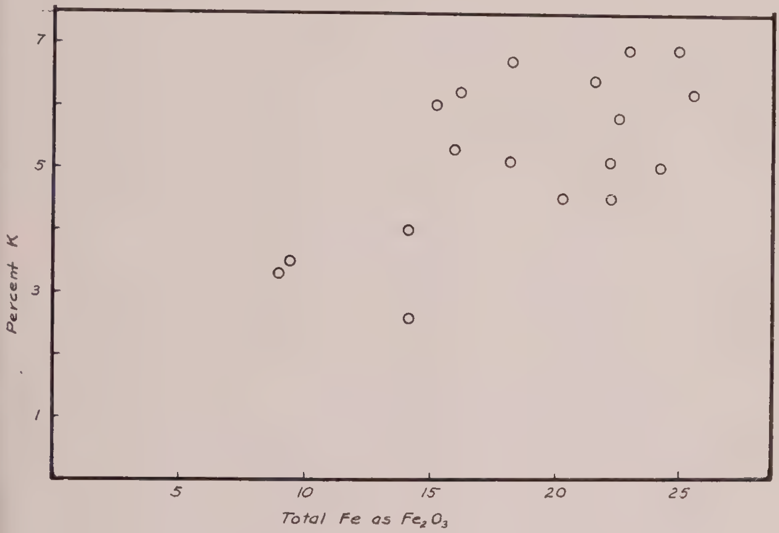

FIG. 6. The relationship between potassium and iron in glauconite pellets.

owever, if the structural formulas are close to reality, the relationships re valid. Another feature that suggests that the increase in lattice charge predominantly in the octahedral layer is that the mean octahedral harge (−0.92) in glauconite is higher than for any other 2:1 clay min-ral.

To summarize, the data reported in the previous section lend support Burst's model for glauconitization. The model is as follows: (1) the arent material can be any degraded 2:1 layer lattice mineral (except hose with a high net lattice charge); (2) the material must be subjected locally reducing conditions in a generally oxidizing environment—his usually occurs in fecal pellets, foraminiferal fillings, etc.; (3) an bundant supply of K and Fe must be present. This condition is met in e marine environment and not in fresh water environments; (4) glau-onitization proceeds by the slow substitution of iron in the octahedral

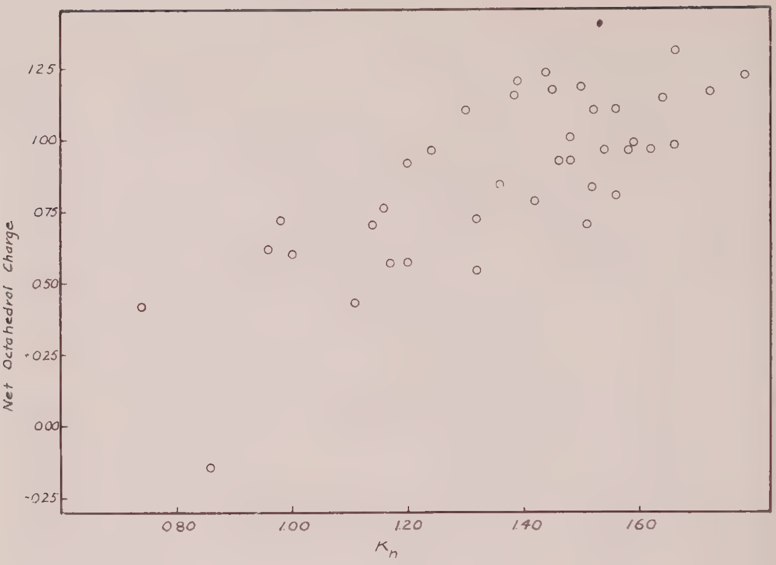

FIG. 7. The relationship between net octahedral charge and the number of potassium ions per unit cell in glauconites.

layer, usually displacing aluminum. Along with this substitution there is a gradual increase in the lattice charge with the consequent uptake of more potassium and the eventual collapse of increasing amounts of layers to 10 Å. The end product is high in iron and potassium and the structure consists mainly of non-expandable 10 Å layers.

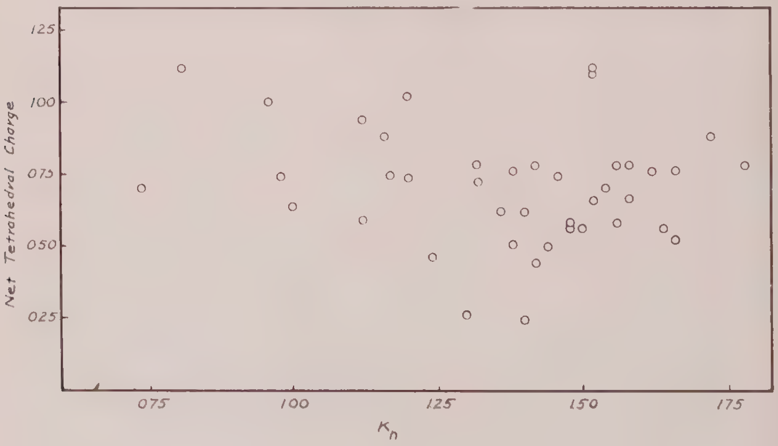

FIG. 8. The relationship between net tetrahedral charge and the number of potassium ions per unit cell in glauconites.

Other factors such as temperature and sedimentation rate will control the rate of the chemical reactions and also determine how far the reaction proceeds before it is stopped. This gives rise to the serial relation in composition and structure found in glauconites. One end of this series approaches a 2:1 layer lattice low in iron and potassium and high in aluminum and has a high percentage of expandable layers; the other end reaches the "mineral glauconite" which is high in iron and potassium, low in aluminum, and has a low percentage of expandable layers.

VARIATIONS IN GLAUCONITE STRUCTURE AND COMPOSITION WITH GEOLOGIC TIME

Several writers (Warshaw, 1957, Conway, 1942, and Smulikowski, 1954) have commented on the variations of glauconite composition with geologic times. Warshaw found no apparent changes. However, both Conway and Smulikowski noted a potassium "deficiency" in Tertiary and Recent glauconites. Table IV is a summary taken from the data in Table I, of the means and ranges of per cent expandable layers and per cent potassium for different portions of geologic time. The potassium analyses are reported only for non-mixed-mineral glauconites. Quite apparent differences in structure and composition occur between Early Paleozoic (Cambrian through Devonian) and all younger glauconites. Glauconites younger than Devonian average considerably less potassium and consequently have a more expandable structure. These data substantiate a potassium "deficiency" in young glauconites. Both Conway and Smulikowski have proposed explanations for this potassium deficiency. Smulikowski interprets it as the result of changes in the chemical environment of the ocean; Conway further proposes that this difference in environment is a result of a potassium deficiency in Tertiary and Recent seas. There is, however, an alternate, simpler, explanation based on the relationship between glauconite type and lithology of the

TABLE IV. SUMMARY OF THE STRUCTURE AND COMPOSITION OF GLAUCONITES OF DIFFERENT GEOLOGIC AGES

Geologic age	No. of samples	Per cent expandable layers		Per cent K		No. of K Anal.
		Mean	Range	Mean	Range	
Early Paleozoic	14	<10	< 5–15	6.1	4.9–6.9	11
Late Paleozoic and Mesozoic	17	~20	10–30	4.8	3.3–6.2	8
Cenozoic	19	~25	10–40	4.3	2.3–6.2	9

enclosing sediment, pointed out in a previous section. Most Early Paleozoic glauconites that have been sampled occur in orthoquartzites and normal carbonate rocks; most Mesozoic and younger glauconites occur in argillaceous sandstones and marls. Hence the structural and compositional relationship with geologic time.

Even though the relationship between glauconite structure and composition and lithologic type seems to provide an adequate explanation for the potassium deficiency in young glauconites, the possibility of epigenetic gain of some potassium in Lower Paleozoic glauconites cannot be excluded. Some data indicate the possibility of epigenetic gain of potassium: (1) Four of the eleven Lower Paleozoic glauconites analyzed for potassium are higher in potassium than any younger glauconite; (2) Three Lower Paleozoic glauconites were sampled from argillaceous sandstones (sample numbers 14, 16, and 17), and have the least amount of expandable layers (15 per cent) of all glauconites occurring in argillaceous sandstone.

TABLE V. FREQUENCY OF OCCURRENCE OF MIXED-MINERAL GLAUCONITES AS RELATED TO GEOLOGIC AGE

Geologic	No. of Samples	No. of Mixed-Mineral Glauc.	Frequency	Lithologic Types
Lower Paleozoic	14	1	0.07	arg. ss
Upper Paleozoic and Younger	23	8	0.35	4 arg. ss 4 marls

Another interesting mineralogical feature of glauconites is the frequency of occurrence of the "mixed-mineral" type of glauconite pellets (Burst's type four) in different portions of geologic time. Table V is a summary of the known data from Lower Paleozoic and from Upper Paleozoic (Mississippian on up) and younger glauconites. The frequency of occurrence of mixed mineral glauconites in Lower Paleozoic glauconites is strikingly lower than the frequency in younger glauconites. Assuming a χ^2 distribution, this has one degree of freedom and $\chi^2 = 3.94$ and a relationship can be rejected at the 0.05 level.

Kaolinite and chlorite appear to be the usual extraneous clay minerals present in glauconite pellets (Burst, 1958*a*). However, it is possible that many glauconites contain illite as a "contaminant." The structure of illite is the same as that of glauconite, hence the detection of illite contamination is difficult or impossible. It is possible that some "aluminous" glauconites with a low per cent of expandable layers are actually illite contaminated. On the other hand, it can be pointed out that the relationship etween the iron and aluminum content of glauconite and the per cent expandable layers indicates that the effect of illite contamination, if ny, is masked.

Though the data are limited, it can be seen from Table V that, as with he variability in per cent expandable layers, the occurrence of mixed-mineral pellets appears to be related to the lithologic type of the enclosing sediment. All the mixed-mineral glauconites occur either in argillaceous sandstones or marls. No mixed-mineral pellets have been found to occur n orthoquartzites or normal carbonate rocks. Also, extraneous clay minerals occur only in pellets in which the interlayered illite-montmorillonite-type structure contains ≥15 per cent expandable layers. The relationship could be explained in two possible ways: (1) The mixed-mineral pellets were formed from a different (more heterogenous) source material from non-mixed-mineral pellets; (2) The extraneous clay minrals are eliminated in some manner during the glauconitization process, eaving a simpler mineralogy. It would also seem likely, because of their ympathetic variation, that the differences in interlayering and the resence or absence of extraneous clay minerals have a common cause.

The problem of the variations in the chemical composition and strucure of glauconite pellets with geologic age is a very interesting one, pecially in the light of the fact that the temporal variations are very milar to the changes that have been found for clay mineral assemblages shales. Weaver (1958*a*) has shown abundant evidence indicating that change in the clay mineral composition of shales takes place within e Mississippian Period. Illite is the dominant clay mineral of pre-pper Mississippian sediments. Post-Lower Mississippian clay mineral ssemblages tend to be more complex; illite is less abundant and kao- nite and expandable clays (including mixed-layer illite/montmorillo- te) are more abundant.

The relation between the clay mineralogy of glauconite pellets and ologic age is as follows. The clay mineral assemblages of glauconite ellets in the Lower Paleozoic are almost always monomineralic interyered illite-montmorillonite structure averaging less than 10 per cent pandable layers. The mineralogy of Upper Paleozoic and younger lauconite pellets is more complex in that the pellets frequently contain traneous clay minerals and significantly more expandable material 0–25 per cent). A summary of the comparison of clay mineral suites nd glauconite pellet mineralogy of different geologic ages is shown in able VI.

Weaver (1958*b*) has shown quite convincingly that the clay mineral mposition of Recent sediments strongly reflects the source material. e has further argued that this relationship can be applied to all sediments since the beginning of the Paleozoic. In other words, he has concluded that clay minerals have a detrital origin and owe little of their character to diagenetic changes. The chemical changes that Weaver agrees can take place involve only the interlayer cations and not the ions present in the basic lattice –those in octahedral and tetrahedral coordination.

Weaver (1958*b*) has also concluded that source material determines the mineralogical character of glauconite pellets. It cannot be denied that the mineralogical character of glauconite pellets reflects, in part, the source material. For example, it seems quite certain that the tetrahedral charge and composition of the interlayered illite-montmorillonite clay in glauconite pellets—that material of which most pellets are exclusively composed—is inherited from the source. However, striking changes do take place in the basic lattice involving ions in the octahedral layer. The present writer believes that the evidence given by Burst (1958*a*, 1958*b*) and in this paper shows that the nature of the interlayered illite-montmorillonite in glauconite pellets is determined overwhelmingly by diagenetic changes and the resulting mineralogy reflects little of the original character of the source material. The conclusions concerning the reason for the presence or absence of extraneous clay minerals cannot be stated so strongly. However, since most glauconite pellets (regardless of geologic age) are monomineralic it appears quite likely that the glauconitization process tends to eliminate these clays. Monomineralic pellets frequently occur in matrix of heterogeneous clay minerals. As Burst (1958*a*) has pointed out, "to prescribe . . . a 'detrital' background for the argillaceous material in fecal pellets would be to prescribe an organism which is capable of selecting only single-layer, monoclinic, dioctahedral crystal fragments from among the innumerable diet possi-

TABLE VI. COMPARISON OF THE MINERALOGY OF GLAUCONITE PELLETS AND THE CLAY MINERAL ASSEMBLAGES OF SHALES OF DIFFERENT GEOLOGIC AGES

Geologic Age	Abundance of Expandable Material		Complexity of Clay Mineral Assemblage	
	Clay Mineral Suites	Glauconite Pellets	Clay Mineral Suites	Glauconite Pellets
Pre-Upper Mississippian	illite the dominant clay; little expandable material	Ave. <10% expandable layers in interlayered illite/montmorillonite	Generally simple	Frequency of occurrence of mixed-mineral pellets 0.07
Post-Lower Mississippian	illite less abundant; expandable clays more abundant	Ave. 20–25% expandable layers in interlayered illite/montmorillonite	More complex, containing more kaolinite and expandable clays	Frequency of occurrence of mixed-mineral pellets 0.35, kaolinite and chlorite the extraneous clays

bilities on the ocean floor.'' Additional evidence that points to the probability that extraneous clay minerals are eliminated during glauconitization is that extraneous clays occur only in pellets in which the interlayered illite/montmorillonite contains ≥15 per cent expandable layers —those pellets which have undergone the least glauconitization. Of course, it is possible that both processes have been operative; i.e., younger sediments have more heterogeneous sources and thus the glauconitization process has not been able to eliminate extraneous clay minerals from pellets as efficiently as in the Lower Paleozoic.

Conclusions

To summarize, it seems that glauconitization—which is a diagenetic process—determines the bulk of the chemical and structural properties of the clay minerals in glauconite pellets. Glauconitization involves large chemical changes in the basic lattice and interlayer cations of the predominant illite/montmorillonite clay that occurs in glauconite pellets and appears to eliminate extraneous clay minerals. The mineralogy of glauconite pellets is changed radically from the mineralogy of the source material. Therefore, since the clay mineralogy of glauconite pellets shows changes with geologic time that are very similar to those changes exhibited by the clay mineral suites of shales, it is tempting to suggest that Weaver has not given enough credit to the effect of diagenesis in the formation of clay mineral assemblages.

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References

rown, G., and MacEwan, D. M. C. (1951) X-ray diffraction by structures with random interstratification: in Brindley, G. W., *X*-ray identification and crystal structure of clay minerals, Chap. XI, 266–284, *Mineral Soc. Great Gritain Mono.*

urst, J. F. (1958a) "Glauconite" pellets: their mineral nature and applications to stratigraphic interpretations: *A.A.P.G. Bull.*, **42,** 310–327.

— — (1958b) Mineral heterogeneity in "glauconite" pellets: *Am. Mineral.*, **43,** 481–49.

loud, P. E. (1955) Physical limits of glauconite formation: *A.A.P.G. Bull.*, **39,** 484–492.

onway, E. J. (1942) Mean geochemical data in relation to oceanic evolution: *Proc. Royal Irish Acad.*, **48,** 119–212.

Galliher, E. W. (1935) Glauconite genesis: *Bull. Geol. Soc. Amer.*, **46**, 1351–1366.

——— (1939) Biotite-glauconite transformation and associated minerals: *Recent Marine Sediments*, A.A.P.G., 513–515.

Hendricks, S. B., and Ross, C. (1941) Chemical composition and genesis of glauconite and celadonite, *Am. Mineral.*, **26**, 683–708.

Herzog, L. F., Pinson, W. H., and Cormier, R. F. (1958) Sediment age determination by Rb/Sr analysis of glauconite: *A.A.P.G. Bull.* **42**, 717–733.

Hoebeke, F., and Dekeyser, W. (1955) La glauconite: *Comptes Rendus de Recherches, IRSIA*, **14**, 102–121.

Hower, J., (1959) Matrix corrections in the x-ray spectrographic trace element analysis of rocks and minerals: *Am. Mineral.*, **44**, 19–32.

Hurley, P. M., Fairbairn, H. W., and Pinson, W. H. (1959) Variations in isotopic abundances of strontium, calcium, and argon and related topics: *Seventh Annual Prog. Rept., USAEC Contract AT(30–1)*—1381, 11–22.

Johns, W. D., and Grim, R. E. (1958) Clay mineral composition of recent sediments from the Mississippi River Delta: *Jour. Sed. Petrol.*, **28**, 186–199.

Kinter, E. B., and Diamond, S. (1956) A new method for preparation and treatment of oriented-aggregate specimens of soil clays for x-ray diffraction analysis: *Soil Science*, **81**, 111–120.

Reynolds, R. C. (1959) Geochemical method for determining paleosalinity: *Eighth Nat. Conf. Clays and Clay Min.*, abstract.

Smulikowski, I. (1954) The problem of glauconite: *Polska Akad. Nauk Kom. Geol. Arch.-Mineral*, **18**, 21–120.

Takahaski, J., and Yagi, T. (1929) Peculiar mud grains and their relation to the origin of glauconite: *Econ. geol.*, **24**, 838–852.

——— (1939) Synopsis of glauconitization: *Recent Marine Sediments*, A.A.P.G., 503–512.

Warshaw, C. M. (1957) The mineralogy of glauconite: unpublished Ph.D. thesis, Penn. State Univ.

Weaver, C. E. (1956) The distribution and identification of mixed-layer clays in sedimentary rocks: *Am. Mineral.*, **41**, 202–221.

——— (1958a) The clay petrology of sediments: *Proc. Sixth Nat. Conf. Clays and Clay Min.*, Pergamon Press, 154–187.

——— (1958b) Geologic interpretation of argillaceous sediments: *A.A.P.G. Bull.*, **42**, 254–309.

——— (1958c) The effects and geologic significance of potassium "fixation" by expandable clay minerals derived from muscovite, biotite, chlorite, and volcanic material: *Amer. Mineral.*, **43**, 839–861.

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THE COMPOSITION OF THE ALUMINIAN LUDWIGITE FROM CRESTMORE, CALIFORNIA*

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ABSTRACT

The black crystals of the aluminian ludwigite (Woodford's mineral B) from the limestone at Crestmore, California, gave on analysis: $B_2O_3=18.15$, $MgO=40.67$, $FeO=5.60$, $MnO=0.02$, $Al_2O_3=10.97$, $Fe_2O_3=22.59$, $TiO_2=1.50$, $SnO_2=0.24$, $H_2O-=0.07$, $H_2O+=0.05$, insoluble$=0.48$; total$=100.34$ per cent. Specific gravity 3.64. The formula is $(Mg_{3.80}, Fe^{+2}_{0.29})$ $(Al_{0.81}, Fe^{+3}_{1.06}, Ti_{0.07}, Sn_{0.01})$ $B_{1.96}O_{10}$ or essentially $Mg_2(Fe^{+3}, Al)BO_3O_2$. This ludwigite has the highest known content of Al_2O_3 of any member of the ludwigite ($Mg \gg Fe^{+2}$)-vonsenite ($Fe^{+2} \gg Mg$) series.

The black crystals of ludwigite in the limestone at Crestmore, California, have been known for some time to contain an unusually high percentage of aluminum for a ludwigite. An unpublished spectrographic analysis by T. G. Kennard indicated a high percentage of Al_2O_3 as did an incomplete chemical analysis by J. D. Laudermilk whose results showed that the mineral was an anhydrous iron (mostly ferric with only few per cent of FeO) magnesium borate and identified the mineral as ludwigite (A. O. Woodford, written communication).

This ludwigite is Woodford's mineral B. Woodford, Crippen, and Garner (1941, p. 375) state "Slender, black orthorhombic prisms up to [illegible] mm. in length have been found in the Sky Blue limestone (*e.g.* at station 31, Wet Weather quarry)." (The thickest single crystal observed by W.T.S. is 2 mm. thick.) Woodford (1943) gives the optical properties as X = pale green, Y = slightly darker green, Z = dark brown. The alpha index of refraction is given as 1.791, probably ±0.002 and the birefringence $(\gamma\text{-}\alpha)=0.095\pm0.010$, hence $\gamma=1.886\pm0.010$.

Because of the aluminum present these values are considerably lower than those given for several ludwigites by Larsen (1921).

This occurrence differs from nearly all other occurrences of ludwigite in that the mineral is present in the limestone as single isolated crystals, mostly with many brilliant faces in the prism zone. Edgar H. Bailey, U. S. Geological Survey, also observed and measured goniometrically some crystals with terminal faces (Woodford, 1943). The usual mode of occurrence of ludwigite as finely fibrous masses, with either parallel or interwoven or radiating fibers apparently is not known for Crestmore.

A suite of the limestone specimens containing this ludwigite was sent to Schaller by Edgar H. Bailey some years ago and furnished the material used for the analysis presented here. Single larger crystals of ludwigite

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* Publication authorized by the Director, U. S. Geological Survey.

are sparsely and irregularly distributed throughout the limestone although occasionally several crystals may be grouped together and aggregates of very minute crystals occasionally are present, especially where associated with colored silicates. Very minute and long hairlike crystals are closely associated with the larger ones or may be present by themselves. Some of the crystals are apparently deeply etched whereas others seem to be the result of skeletal growth. Long curved forms of ludwigite are present at many places; if the two ends meet they will enclose limestone.

In the preparation of material for analysis, a total weight of two kilograms of the limestone was dissolved in cold 1:3 HNO_3, yielding $78\frac{1}{2}$ grams of insoluble material of which $9\frac{1}{2}$ grams, or about 12 per cent, was ludwigite. The remainder was chiefly forsterite and a humite group mineral, probably clinohumite. No other acid insoluble borate mineral was noted. The two kilograms of limestone therefore consisted approximately of 96% carbonate, $3\frac{1}{2}$% acid insoluble silicates, and $\frac{1}{2}$% ludwigite. Even this low percentage of ludwigite is high for its per cent occurrence in large masses of the limestone as only the richest portions of the limestone were used. To the ludwigite crystals so obtained were added several grams of additional material previously separated and purified by Edgar H. Bailey. Before the separated crystals obtained from the limestone were crushed, several dozen of the best crystals were selected by handpicking and preserved for goniometric measurement. It was from this lot of crystals that those used in the crystal structure studied by da Silva, Clark, and Christ (1955) were selected.

For the final purification of the Crestmore ludwigite the electromagnet, isodynamic separator, methylene iodide, and handpicking were all used. In washing out the dust of the crushed sample, the wash water appeared greenish (olive-green) due to the translucency of the dust particles. This translucency indicates a low content of FeO in the ludwigite. The analyzed sample is not magnetic, that is, it does not move when tested with a small alnico magnet.

The analysis presented no unusual difficulty although the values obtained for MgO are a little high due probably to the inclusion in the ludwigite crystals of a little periclase or brucite, as discussed below.

The results of the analysis are given in Table 1.

The present analysis differs from those of other low FeO ludwigites in its high percentage of Al_2O_3 (and correspondingly low Fe_2O_3). Many analyses of ludwigite show small amounts of Al_2O_3, usually from 1 to 3 per cent. The relatively large amount of TiO_2 present is surprising as no other titanium mineral has been noted from the Crestmore limestone, although golden yellow sphene is reported by Woodford (1943, p. 360) as

TABLE 1. ANALYSIS OF ALUMINIAN LUDWIGITE FROM CRESTMORE, CALIFORNIA
Analyst, Angelina C. Vlisidis

				Average
B_2O_3	18.29%	17.91%	18.26%	18.15%
MgO	40.86	40.48	40.66	40.67
FeO	5.59	5.62	5.60	5.60
MnO	.01	.03	—	.02
Al_2O_3	11.02	10.92	—	10.97
Fe_2O_3	22.56	22.61	—	22.59
TiO_2	1.50	1.50	—	1.50
SnO_2	.31	.17	—	.24
H_2O^-	.07	—	—	.07
H_2O^+	.05	—	—	.05
CaO	None	—	—	None
Insoluble	.50	.54	.41	.48
				100.34

Specific gravity 3.64.

Total Fe as $Fe_2O_3=28.78$, 28.93, average 28.86 per cent.

Total R_2O_3 (gravimetric) $=41.28$ per cent which agrees well with the sum of 28.86 total n $+10.97$ $Al_2O_3+1.50$ $TiO_2=41.33$.

ing “very abundant in some pegmatites. Larger brown crystals are so fairly common.”

The atomic ratios calculated from the average analysis are given in able 2.

The formula is calculated from the analysis on the basis that the for-ula contains 10 oxygen atoms, that is, a total charge of -20. The uivalent e is defined as,

$$e=\frac{\text{formula weight}}{\text{valence of cation}\times\text{number of cations in formula}}.$$

he factor $f=20/\sum e$ is an average common multiplier such that $=f\times e$ yields the total positive charge in each individual oxide; /(valence of cation) is the number of cations.

These ratios are close to the standard formula of ludwigite, $RO\cdot R_2O_3\cdot B_2O_3$. That of the bivalent group is a little high. The ratios B (1.96) and of the sum of Al, Fe^{+3}, Ti, Sn (1.95) are so nearly identical at it would seem as if a small quantity (estimated as less than one per nt) of an acid-soluble magnesium-rich second phase (periclase?, ucite?) was present in the sample, as an undetected impurity, account-g for the high ratio (4.09) of the bivalent elements Mg, Fe^{+2}, Mn. Ob-rvation of a polished mount of many fragments of the ludwigite crys-

TABLE 2. ATOMIC RATIOS CALCULATED FROM AVERAGE ANALYSIS OF ALUMINIAN LUDWIGITE FROM CRESTMORE, CALIFORNIA

	Analysis	e	$e'=3.764\times e$	Atomic ratios		
B_2O_3	18.15%	1.563	5.885	B		$1.96=2\times0.98$
MgO	40.67	2.017	7.594	Mg	3.80	
FeO	5.60	.156	.587	Fe^{+2}	.29	$4.09=4\times1.02$
MnO	.02	.001	.002	Mn	.00	
Al_2O_3	10.97	.646	2.431	Al	.81	
Fe_2O_3	22.59	.849	3.194	Fe^{+3}	1.06	$1.95=2\times0.98$
TiO_2	1.50	.075	.283	Ti	.07	
SnO_2	.24	.006	.024	Sn	.01	
	99.74	5.313	20.000			
H_2O^-	.07					
H_2O^+	.05					
CaO	.00			$f=\frac{20}{5.313}=3.764$		
Insoluble	.48					
	100.34					

$(Mg_{3.80}, Fe^{+2}_{0.29})(Al_{0.81}, Fe^{+3}_{1.06}, Ti^{+4}_{0.07}, Sn^{+4}_{0.01})(B_{1.96}O_6)O_4.$

tals as well as a thin section of the limestone carrying the ludwigite shows several colorless inclusions completely embedded in the ludwigite and hence not amenable to nitric acid attack until the surrounding ludwigite is dissolved away.

On a weight percentage basis the composition of this ludwigite can be interpreted to be approximately:

48½ per cent	MgO-Fe_2O_3 borate
36½ per cent	MgO-Al_2O_3 borate
10 per cent	FeO-Fe_2O_3 borate
4½ per cent	MgO-TiO_2 borate
½ per cent	MgO-SnO_2 borate

The ludwigite-vonsenite series must then be considered at least a three component system $4MgO\cdot Fe_2O_3\cdot B_2O_3$, $4MgO\cdot Al_2O_3\cdot B_2O_3$, and $4FeO\cdot Fe_2O_3\cdot B_2O_3$.

Five boron minerals are known from Crestmore. Axinite has been described by Eakle (1917). Murdoch and Webb (1940, p. 553) state "The axinite [from Inyo County] looks almost exactly like that found at Crestmore, in Riverside County, California." Axinite was also listed by Woodford (1943) as were danburite, datolite, ludwigite, and tourmaline. Axinite, datolite, and tourmaline are also mentioned by Burnham (1959) as occurring at Crestmore. Two other borate minerals, serendibite

(Richmond, 1939) and vonsenite (Eakle, 1920), apparently as yet not reported for Crestmore, occur in the several other limestone quarries surrounding Riverside.

References

Burnham, C. W. (1959), Contact metamorphism of magnesian limestones at Crestmore, California: *Geol. Soc. America Bull.* **70**, 879–919.

da Silva, J. C., Clark, J. R., and Christ, C. L. (1955), Crystal structure of ludwigite $Mg_2Fe'''BO_3O_2$ (abs.): *Geol. Soc. America Bull.*, **66**, 1540–1541.

Eakle, A. S. (1917), Minerals associated with the crystalline limestone at Crestmore, Riverside County, California: *California Univ. Dept. Geol. Bull.*, **10**, 350.

——— (1920), Vonsenite; a preliminary note on a new mineral: *Am. Mineral.*, **5**, 141–143.

Larsen, E. S. (1921), The microscopic determination of the nonopaque minerals: *U. S. Geol. Survey Bull.*, **679**, 102, 103.

Murdoch, Joseph and Webb, R. W. (1940), Notes on some minerals from southern California. II: *Am. Mineral.*, **25**, 549–555.

Richmond, G. M. (1939), Serendibite and associated minerals from the New City quarry, Riverside, California: *Am. Mineral.*, **24**, 725–726.

Woodford, A. O. (1943), Crestmore minerals: *California Jour. Mines and Geology*, **39**, 333–365.

Woodford, A. O., Crippen, R. A., and Garner, K. B. (1941), Section across Commercial quarry, Crestmore, California: *Am. Mineral.*, **26**, 351–381.

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SOME ASPECTS OF THE CALCIFEROUS AMPHIBOLES, OXYHORNBLENDE, KAERSUTITE AND BARKEVIKITE

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ABSTRACT

The brown calciferous amphiboles oxyhornblende, kaersutite and barkevikite have been examined briefly in terms of their chemistry, optical properties and mode of occurrence. The titaniferous amphibole kaersutite, generally considered to be a variety of oxyhornblende, often has low Fe_2O_3/FeO ratios and is therefore distinct from the latter mineral. Kaersutite and barkevikite compositions are dominated respectively by the end-member series pargasite-ferropargasite.

Optical properties of brown amphiboles assigned to the three species show considerable overlap. Birefringences greater than 0.040 characterize true oxyhornblendes.

Kaersutite and barkevikite are the brown calciferous amphiboles typically encountered in undersaturated alkaline rocks, barkevikite possessing higher Fe_2^{+}/Mg ratios than kaersutite, and $Mg<2$ atoms. Kaersutite occurs most commonly in analcite-bearing rocks of wide compositional range, and in nepheline-bearing basic rocks. On the other hand, barkevikite is more characteristic of the nepheline-syenites, and is an iron-enriched amphibole developed as a consequence of relatively less hydrous conditions resulting in increased Fe^{2+}/Mg ratios in the magma.

INTRODUCTION

Questions of nomenclature of oxyhornblende* kaersutite and barkevikite reflect one of the many problems arising from extensive ionic substitution in the calcium-sodium amphibole group. Apart from the problem of identification by optics, actual measurements of optical properties of the three minerals in question are rendered more difficult by their strong brown or reddish-brown absorption colours. And, as emphasized by Boyd (1955), the ways in which the composition of a particular amphibole reflects the chemical and physical environment in which it formed, as yet are not clearly understood.

Amphiboles referred to oxyhornblende, kaersutite and barkevikite have been described from a wide range of igneous rocks. Generally these minerals have been most frequently recognized in alkaline undersaturated types, particularly kaersutite and barkevikite. One feature of their chemistry, namely frequent enrichment in TiO_2, recalls a similar feature of clinopyroxenes of alkali olivine-basalt magma (Wilkinson, 1956, Table 2). In these minerals, TiO_2 contents of 2–4 per cent are not uncommon.

Basaltic hornblende, oxyhornblende (Winchell, 1932, p. 473) and lamprobolite (Rogers, 1940) are synonymous terms to cover the dark brown amphibole with high ferric iron content, high indices of refraction and rather strong to extreme birefringence. A small extinction angle also has been cited as a diagnostic optical property. Both Winchell and Rogers have pointed out the unsatisfactory usage of the term basaltic hornblende to cover an amphibole with these properties, as this mineral is by no means confined to basalts.

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* Throughout this paper the term oxyhornblende is used in preference to the synonymous terms basaltic hornblende and lamprobolite.

The term kaersutite was proposed by Lorenzen (1884) for a highly titaniferous amphibole occurring in feldspathic veins and dikes cutting the picrite at Kaersut, Greenland. Lorenzen's original material was subsequently re-examined by Washington and Wright (1908). The term kaersutite has carried various connotations, *e.g.* a highly titaniferous oxyhornblende (Washington and Wright, 1908, p. 210; Benson, 1940, p. 285; Winchell, 1951, p. 437; Kerr, 1959, p. 330); a rare variety of barkevikite (Yagi, 1953, p. 783) and a brown hornblende with abundance of TiO_2 (Aoki, 1959, p. 278).

Barkevikite (Brögger, 1890) has been variously defined in relation to other amphiboles, e.g. as a member of the oxyhornblendes (Kunitz, 1930, p. 214; Sundius, 1946, p. 30) or the soda amphiboles (Winchell, 1951, p. 440).

Attention has been frequently directed to experiments (*e.g.* Kôzu *et al.*, 1927; Barnes, 1930) whereby green hornblende on heat treatment changes to a mineral having the appearance and optical properties of oxyhornblende. In this transformation, the principal chemical change is oxidation of the ferrous iron and loss of hydrogen. Barnes showed that the principal optical changes associated with heating green hornblende in air at about 800° C. are: increase in the indices of refraction, birefringence and dispersion; decrease in the extinction angle and change in 2V to 65°; change in colour and pleochroism from greens to browns.

CHEMISTRY AND CLASSIFICATION

In recent years the classification of the calciferous amphiboles has been discussed by Hallimond (1943), Winchell (1945), Sundius (1946), Boyd (1959) and Smith (1959). In general, four principal magnesian end-members (plus their ferriferous analogues) have been recognized (Table 1), namely tremolite (-ferrotremolite or actinolite*), edenite

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* The terminology of these two ferriferous end-members varies with different authors. In this paper the term ferropargasite is preferred for the pure ferriferous end-member equivalent of pargasite, inasmuch as the term hastingsite for many years has referred to Fe-rich amphiboles with small amounts of MgO, or else to various calciferous amphiboles with variable FeO/MgO ratios (Billings, 1928). The term ferrotremolite is preferred for the Fe-analogue of tremolite.

(-ferroedenite), tschermakite (-ferrotschermakite) and pargasite (-ferropargasite or hastingsite*). The most significant end-member series in the present discussion is the pargasite-ferropargasite series, the Mg end-member pargasite $NaCa_2Mg_4Al^{VI}Al_2^{IV}Si_6O_{22}(OH)_2$ being derived from tremolite $Ca_2Mg_5Si_8O_{22}(OH)_2$ by the double substitution AlAl for MgSi and NaAl for Si.

Boyd (1959, p. 382) has shown graphically that the two most important end-member series of the calciferous amphiboles (including the more familiar green igneous hornblendes) are $Ca_2FM_5Si_8O_{22}(OH)_2$ and $(Na, K)Ca_2FM_4(Al^{VI}, Fe^{3+})Al_2^{IV}Si_6O_{22}(OH)_2$, where $FM = Fe^{2+} + Mg$. The amphiboles considered by Boyd had $Ca = 1.8$–2.1 and low contents of Ti (<0.20).

TABLE 1. END-MEMBERS OF CALCIFEROUS AMPHIBOLES

tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$
ferrotremolite actinolite	$Ca_2Fe_5Si_8O_{22}(OH)_2$
pargasite	$Na\ Ca_2Mg_4Al^{VI}Al_2^{IV}Si_6O_{22}(OH)_2$
ferropargasite hastingsite	$Na\ Ca_2Fe_4^{2+}Al^{VI}Al_2^{IV}Si_6O_{22}(OH)_2$
edenite	$Na\ Ca_2Mg_5Al^{IV}Si_7O_{22}(OH)_2$
ferroedenite	$Na\ Ca_2Fe_5^{2+}Al^{IV}Si_7O_{22}(OH)_2$
tschermakite	$Ca_2Mg_3Al_2^{VI}Al_2^{IV}Si_6O_{22}(OH)_2$
ferrotschermakite	$Ca_2Fe_3^{2+}Al_2^{VI}Al_2^{IV}Si_6O_{22}(OH)_2$

Tables 2–4 list analyses of amphiboles assigned by various workers to oxyhornblende, kaersutite and barkevikite respectively. In Table 5, these amphiboles have been recalculated on a basis of 24 (O, OH, F). Much of this latter data has been taken from Hallimond (1943, Table 1). An uncertainty in these calculations is the determination of H_2O^+, and non-determination of F, particularly in older analyses. Only analyses showing reasonably close agreement with the general calcium-sodium amphibole formula $W_{2-3}(XY)_5Z_8O_{22}(OH)_2$* have been listed. Many analyses were rejected because of significant departures of the W (where greater than 3.2) and XY (greater than 5.4) groups.

In the three amphiboles, Si is close to 6 atoms, associated with two Al atoms in four-fold co-ordination. Ca is generally 1.8–2.0. In five cases there is insufficient aluminium to satisfy the Al^{IV} requirements in the

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* W = (Na, K, Ca), X = (Mg, Fe_2^+, Mn), Y = (Al^{VI}, Fe^{3+}, Ti), Z = (Si, Al^{IV}).

	1	2	3	4	5	6	7	8	9	10
SiO_2	40.17	39.83	39.85	39.96	42.05	39.82	41.97	39.48	40.69	45.17
TiO_2	3.78	2.56	4.25	4.05	1.80	2.42	4.20	3.10	2.98	2.11
Al_2O_3	15.09	14.98	13.07	12.83	12.59	12.34	12.59	10.97	12.09	7.68
Fe_2O_3	5.49	7.66	6.76	7.40	8.61	11.86	4.69	11.23	11.83	14.30
FeO	5.99	3.78	5.09	6.37	6.45	8.02	5.80	8.21	0.21	2.81
MnO	0.09	—	—	—	—	—	n.d.	0.53	0.70	0.41
MgO	12.48	14.44	13.58	12.92	12.40	9.78	14.20	10.30	14.34	13.44
CaO	11.21	12.39	12.42	12.07	12.28	12.26	11.99	13.65	11.85	11.18
Na_2O	2.27	2.27	2.79	2.28	2.03	2.28	3.17	0.99	2.45	1.35
K_2O	1.55	1.25	0.98	1.48	0.87	1.03	1.63	0.67	1.56	1.09
H_2O^+	2.10	0.58	0.66	0.72	0.63	0.45	0.26	1.49}	1.24}	0.19
H_2O^-	0.25	—	—	—	—	—	—			0.06
F	—	—	—	—	—	—	n.d.	—	—	0.35
etc.	—	—	—	—	—	—	—	0.24	0.10	—
Less O=F	100.47	99.74	99.45	100.08	99.71	100.26	100.50	100.86	100.04	100.14 0.14
Total	100.47	99.74	99.45	100.08	99.71	100.26	100.50	100.86	100.04	100.00
α	1.670	1.667	1.677	1.679	1.668	1.681	1.675	—	1.685	1.675
β	1.682	—	—	—	—	—	1.691	—	1.711	1.715
γ	1.693	1.688	1.700	1.701	1.688	1.700	1.701	—	1.731	1.735
$\gamma-\alpha$	0.023	0.021	0.023	0.022	0.020	0.019	0.026	—	0.016	0.060
$2V_\alpha$	82	—	—	—	—	—	—	—	82	large
$\gamma \wedge c$	9	3	6	—	—	0	11–12	2–10	0–2	5
Pleochroism										
X	Pale yellow with tinge of brown	—	—	—	—	—	—	—	amber yellow	pale yellow
Y	dark brown	brownish green	brown	brown	greenish brown	brown	"scarcely noticeable pleochroism"	—	yellowish brown	dark chestnut brown
Z	dark olive green with tinge of brown	—	—	—	—	—	—	—	reddish nrown	dark chestnut brown
Absorption	$X<Y<Z$	—	—	—	—	—	—	—	$X<Y<Z$	$X<Y<Z$

1. From tuff-breccia, L. Balaton, Hungary (Vendl, 1924, p. 238).
2. From tephrite, Grosspriessen, Bohemia (Kunitz, 1930, p. 245).
3. From trachydolerite, Madeira (Kunitz, 1930, p. 245).
4. From volcanic-bomb, "Isleta-Krater" (Kunitz, 1930, p. 245).
5. From gabbro, "S. Vincent" (Kunitz, 1930, p. 245).
6. From essexitic phonolite, "Tejedatal" (Kunitz, 1930, p. 245).
7. From sodic lava, Kilimanjaro, E. Africa (Washington and Merwin, 1922, p. 124).
8. From hypersthene-andesite, Shabō-zan, Taiwan (Ichimura, 1931, p. 564).
9. From hypersthene-andesite, Shabō-zan, Taiwan (Ichimura, 1931, p. 564. Note: this amphibole referred to brown hornblende by the author. Winchell, 1945, Table 4, treats it as an oxyhornblende).
10. From quartz-latite, San Juan region, Colorado (Larsen *et al.* 1937, p. 895. Analysis calculated to 100 per cent from material with 0.79 per cent P_2O_5).

TABLE 3. CHEMICAL ANALYSES AND OPTICAL PROPERTIES OF KAERSUTITE

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	39.30	39.50	40.73	39.51	41.46	40.36	39.78	39.20	39.01	38.30	39.68	40.85
TiO_2	10.25	10.33	8.47	5.64	5.70	7.09	7.00	6.53	6.05	6.02	7.12	8.47
Al_2O_3	11.16	11.12	10.62	14.26	14.24	13.78	14.13	13.87	13.60	12.87	12.81	9.89
Fe_2O_3	1.21	0.06	1.39	1.75	3.32	3.39	4.61	4.03	5.25	7.98	4.04	8.85
FeO	8.76	9.44	11.91	10.92	5.70	7.91	7.31	7.33	7.42	6.96	8.79	3.96
MnO	0.06	0.10	0.25	0.09	0.08	0.14	0.12	0.11	0.14	0.12	0.16	0.12
MgO	13.24	12.90	10.46	11.36	13.68	11.08	11.01	11.96	11.73	11.79	11.22	12.47
CaO	11.29	10.91	10.40	10.12	11.62	10.82	10.75	12.37	12.05	10.47	11.06	12.16
Na_2O	2.93	3.82	2.92	2.80	2.29	2.78	2.57	1.99	2.51	3.11	3.37	2.01
K_2O	1.06	1.43	1.33	1.59	1.72	1.34	1.58	1.45	1.11	1.30	1.04	0.63
H_2O^+	0.59	0.59	1.97	1.68	0.12	0.79	0.37	0.87	0.98	1.10	0.78	0.19
H_2O^-	—	—	0.23	nil	—	0.26	0.22	0.27	0.19	0.26	0.15	—
F	—	—	—	abs.	0.42	0.37	—	—	abs.	0.05	0.33	0.28
etc.	0.32	—	—	0.09	—	—	—	—	0.09	—	—	0.10
Less O = F	100.17	100.20	100.68	99.81	100.35	100.65	99.45	99.98	100.13	100.33	100.55	99.98
					0.18	0.16				0.02	0.14	0.12
Total	100.17	100.20	100.68	99.81	100.17	100.49	99.45	99.98	100.13	100.31	100.41	99.86
α	1.676	—	α' on (110) 1.680	1.677	1.670	1.688	1.687	1.680	1.682	1.684	1.685	1.692
β	1.694	—	—	1.694	1.692	1.708	1.705	1.700	1.697	1.701	1.710–1.718	1.731
γ	1.708	—	γ' on (110) 1.703	1.707	1.701	1.720	1.718	1.709	1.717	1.720	1.736	1.760
$\gamma-\alpha$	0.032	—	—	0.030	0.031	0.032	0.032	0.029	0.035	0.036	0.051	0.068
$2V_\alpha$ meas.	81	—	77–79	82	81	78	80	75	78	—	74–66	71
$2V_\alpha$ calc.	82	—	—	81	—	—	79	—	—	—	—	80
$\gamma\wedge c$	8	—	16–19	6	8–10	4	4	—	2	3–5	4	1.5
X	—	—	brownish yellow	pale yellowish brown	light yellow brown	pale yellowish brown	pale yellowish brown	—	pale straw brown	—	pale yellowish brown	pale olivine brown
Y	—	—	reddish brown	brown	reddish brown	brown	reddish brown	—	reddish brown	—	brown	brown
Z	—	—	deep chestnut brown with violet tinge	dark brown with reddish tinge	darker reddish brown	dark brown	greenish brown	—	darker reddish brown	—	deep brown	dark brown
Absorption	—	—	X<Y<Z	X<Y<Z	X<Y<Z	X<Y<Z	X<Y<Z	—	X<Y<Z	—	X<Y<Z	X<Y<Z

1. From vein in picrite, Kaersut, Greenland (Washington and Wright, 1908, p. 198).
2. From picrite, Kaersut, Greenland (Gossner and Spielberger, 1929, p. 121).
3. From monzonite, Morotu district, Sakhalin (Yagi, 1953, p. 784).
4. From analcite-basalt, Spring Mount, west of Glen Innes, New South Wales (new analysis).
5. From camptonite, Boulder Dam, Arizona (Campbell and Schenk, 1950, p. 684).
6. From trachyandesite, Gonoura-machi, Iki Islands (Aoki, 1959, p. 279).
7. From kaersutite-basalt dyke (teschenitic), Dôgo, Oki Islands, Japan (Tomita, 1931, p. 103).
8. From volcanic ejectamenta, Uturyo Island, Korea (Harada, 1936, p. 282).
9. From trachybasalt, Leith Valley Quarry, Dunedin, N. Z. (Benson, 1940, p. 286).

TABLE 4. CHEMICAL ANALYSES AND OPTICAL PROPERTIES OF BARKEVIKITE

	1	2	3	4	5
SiO_2	38.41	36.12	40.88	41.12	37.86
TiO_2	1.26	4.82	0.22	0.45	1.25
Al_2O_3	16.39	12.46	11.04	11.02	12.06
Fe_2O_3	3.75	9.60	7.56	6.54	11.47
FeO	21.75	10.43	17.41	17.73	16.23
MnO	0.15	0.28	1.32	1.03	0.82
MgO	2.54	9.09	5.92	6.14	4.03
CaO	10.52	12.01	10.46	10.42	11.43
Na_2O	2.95	2.58	3.75	3.65	2.98
K_2O	1.95	1.41	0.78	0.94	0.72
H_2O^+	0.24	1.02	1.16	1.45	1.23
Total	99.91	99.82	100.50	100.49	100.08
α	—	1.687	1.691	1.687	1.694
β	—	—	—	—	—
γ	—	1.708	1.707	1.701	1.710
γ-α	—	0.021	0.016	0.014	0.015
$2V_\alpha$	—	—	—	—	—
$\gamma \wedge c$	13	10	16	—	20
Pleochroism					
X	yellow brown	—	—	—	—
Y	dark brown	dark brown	dark brown	greenish brown	brown
Z	dark brown	—	—	—	—
Absorption	$X<Y<Z$	—	—	—	—

1. From sodalite-syenite, Square Butte, Montana (Lindgren and Melville, 1892, p. 292).
2. From essexite, Fuerteventura, Canary Isles (Kunitz, 1930, p. 245).
3. From nepheline-syenite, Skuttersundskjär (Kunitz, 1930, p. 245).
4. From nepheline-syenite, Stavarnsjö, Norway (Kunitz, 1930, p. 245).
5. From foyaite, S. Vincente, C. Verde (Kunitz, 1930, p. 245).

Z group, and Ti, apparently replacing Si, has been added to bring this group up to 8.00, as required by the amphibole formula. A comparable procedure has been found necessary in certain titaniferous clinopyroxenes.

Several analyses of kaersutite (Table 3, Analyses 1–4) are significant from the point of view of nomenclature inasmuch as they reveal low Fe_2O_3 contents relative to FeO. The mineral from the type area is included here. This feature of kaersutite chemistry immediately sets it apart from the widely accepted concept of an oxyhornblende. In terms of end members, recalculated analyses of kaersutites with low degrees of oxidation indicate a composition close to that of a titaniferous pargasite with part of the Mg replaced by Fe^{2+}. As an approximation, the composition of the type kaersutite can be written as

TABLE 5. ATOMIC RATIOS OF OXYHORNBLENDE, KAERSUTITE, AND BARKEVIKITE FOR (O, OH, F) = 2400

	Si	Al^{IV}	Al^{VI}	Ti	Fe^{3+}	Fe^{2+}	Mn	Mg	Ca	Na	K	H	F	W	X	Y	XY	Z	(OH, F, Cl)
	Z		Y			X			W										
Oxyhornblende																			
1	585	215	43	41	60	73	1	272	175	64	29	205	—	2.68	3.46	1.44	4.90	8.00	2.05
2	592	208	53	29	86	47	—	321	196	66	24	59	—	2.86	3.68	1.68	5.36	8.00	0.59
3	595	205	25	48	76	74	—	303	199	81	17	67	—	2.97	3.77	1.49	5.26	8.00	0.67
4	599	201	25	46	84	80	—	291	194	66	29	72	—	2.89	3.71	1.55	5.26	8.00	0.72
5	629	171	52	20	97	80	—	278	198	60	17	60	—	2.75	3.58	1.69	5.27	8.00	0.60
6	607	193	25	30	137	103	—	222	201	68	20	46	—	2.89	3.25	1.92	5.17	8.00	0.46
7	622	178	42	47	52	73	n.d.	315	192	92	31	20	—	3.15	3.88	1.41	5.29	8.00	0.20
8	595	195 (Ti 10)	—	25	127	103	7	231	220	29	13	150	—	2.62	3.41	1.52	4.93	8.00	1.50
9	599	201	9	33	131	3	9	315	187	70	29	122	—	2.86	3.27	1.73	5.00	8.00	1.22
10	673	127	8	24	160	35	5	298	178	39	21	19	16	2.38	3.38	1.92	5.30	8.00	0.35
Kaersutite																			
1	573	227	17	112	13	107	8	287	170	83	20	57	—	2.73	4.02	1.42	5.44	8.00	0.57
2	593	196(Ti 11)	—	105	6	118	1	281	176	111	27	59	—	3.14	4.00	1.11	5.11	8.00	0.59
3	604	185(Ti 11)	—	83	16	147	4	233	166	84	25	194	—	2.75	3.84	0.99	4.83	8.00	1.94
4	589	211	39	63	19	136	1	252	162	81	30	167	—	2.73	3.89	1.21	5.10	8.00	1.67
5	612	188	60	63	37	70	1	301	184	65	32	12	20	2.81	3.72	1.60	5.32	8.00	0.32
6	601	199	43	79	38	98	2	246	173	80	25	78	17	2.78	3.46	1.60	5.06	8.00	0.95
7	600	200	51	79	52	92	2	247	174	75	30	37	—	2.79	3.41	1.82	5.23	8.00	0.37
8	587	213	32	73	45	92	1	267	198	58	28	87	—	2.84	3.60	1.50	5.10	8.00	0.87
9	584	216	24	68	59	93	2	262	193	73	21	98	—	2.87	3.57	1.51	5.08	8.00	0.98
10	575	225	2	68	90	87	1	264	168	90	25	110	5	2.83	3.52	1.60	5.12	8.00	1.15
11	594	206	20	80	45	110	2	250	177	98	20	78	16	2.95	3.62	1.45	5.07	8.00	0.94
12	610	174(Ti 16)	—	80	98	46	1	280	196	63	11	20	14	2.70	3.27	1.78	5.05	8.00	0.34
Barkevikite																			
1	614	186	123	15	45	291	2	60	180	91	40	26	—	3.11	3.53	1.83	5.36	8.00	0.26
2	560	228(Ti 12)	—	44	112	135	4	210	199	78	28	106	—	3.05	3.49	1.56	5.05	8.00	1.06
3	629	171	47	3	88	225	17	137	173	111	15	120	—	2.99	3.79	1.38	5.17	8.00	1.20
4	635	165	36	5	77	234	13	143	173	110	19	149	—	3.02	3.90	1.18	5.08	8.00	1.49
5	597	203	21	14	137	217	10	95	187	105	14	128	—	3.06	3.22	1.72	4.94	8.00	1.28

$(Na, K, Ca)_{2-3}(Mg_3, Fe^{2+})\ Ti\ Al_2^{IV}\ Si_6O_{23}(OH)$. In kaersutite the amount of Ti in the Y group is generally between 0.6 and 1. In all cases Mg is greater than 2. Despite variable degrees of oxidation, Fe^{2+} is generally greater than Fe^{3+}.

The analysis of barkevikite cited by Brögger (1890, p. 412) was incomplete. It is characterised by relatively high lime *and* soda (CaO 10.24; Na_2O 6.08 per cent), making it difficult to place in either the calciferous or alkali amphiboles (Miyashiro, 1957, Table 1). Another analysis of barkevikite from the same area (Table 4, Analysis 3) presents no abnormalities in its composition. Compared with kaersutite, barkevikite is characterised by lower contents of Ti and a higher degree of replacement of Mg by Fe^{2+} in the X group, so that Fe^{2+} is generally greater than Mg. In the barkevikite analyses, there is a tendency for the W group to closely approach its maximum value of 3.

It is clear that kaersutite and barkevikite compositions are respectively dominated in their compositions by the pargasite-ferropargasite end-members, in which may be particularly noted the replacement of Al^{VI} by both Ti and Fe^{3+}.

Billings (1928) proposed the following classification of the hastingsite group based on the ratio FeO/MgO (molecular proportions): $FeO/MgO > 2$, ferrohastingsite; $FeO/MgO < 2 > 0.5$, femaghastingsite; $FeO/MgO < 0.5$, magnesiohastingsite. A classification in this manner possesses limitations when, for any reason, oxidation of the iron has taken place. The brown titaniferous (4–7 per cent TiO_2) amphibole from the Mount Royal essexites (Bancroft and Howard, 1923, p. 20), referred to magnesiohastingsite and femaghastingsite by Billings (*op. cit.*), would be regarded as kaersutites by many workers. Sundius (1946, p. 22) has pointed out the similarity of such Mg-rich amphiboles to pargasite.

It is proposed that the chemical distinction between kaersutite and barkevikite be based on the number of Mg atoms in the formula, titaniferous amphiboles with $Mg > 2$ atoms being kaersutites. On this classification the amphibole ($Mg = 2.1$) from the Fuerteventura essexite (Table 4, Analysis 2) would be referred to kaersutite. Barkevikite is analogous in its fundamental chemistry to the TiO_2-poor green or blue-green hastingsites occurring in both acid and over- and undersaturated intermediate rocks.

The term kaersutite has carried with it the implication of a high content of TiO_2, generally greater than 5 per cent. This is perhaps unfortunate, as analogous brown amphiboles with 3–5 per cent TiO_2 are probably not uncommon, particularly in basic alkaline rocks (for example, see Mason, 1958, p. 251). The TiO_2 content of a particular brown amphibole is sensitive to the magma chemistry at the time of its formation. Viewed in this light, there appears to be no reason why brown amphiboles conforming in their essential chemistry to kaersutite but possessing slightly lower TiO_2 contents, should not be covered also by this term. In the writer's opinion, kaersutite should not be regarded as a rare mineral, and it is anticipated that the brown or reddish brown amphibole in intrusive basic alkaline rocks will be of the kaersutite type.

Of those brown amphiboles referred to oxyhornblende, only two (Table 2, Analyses 9 and 10) possess the chemistry and optical properties consistent with oxyhornblende. Of the other amphiboles listed, those types with low birefringences and moderate TiO_2 contents are more akin to kaersutites with moderate degrees of oxidation. Two amphiboles (Analyses 3 and 5) occur in rocks where there is little possibility of the oxyhornblende reaction having occurred (cf. Hallimond, 1943, p. 70). It may be noted that a graphical representation of selected oxyhornblende compositions (Winchell, 1945, p. 45) indicated a tendency for many compositions to plot closest to a $Na\,Ca_2\,(Mg, Fe^{2+})_4\,(Al, Fe^{3+})_3\,Si_6O_{22}\,(OH)_2$ end-member.

OPTICAL PROPERTIES

The optical properties of analyzed amphiboles referred to oxyhornblende or kaersutite (Tables 2 and 3) suggest that the high birefringences (0.05–0.09) measured on brown amphiboles produced in laboratory heating experiments are not frequently attained in natural material. In particular, the frequency with which the optical properties (particularly $\gamma - \alpha = 0.068$) of the Linosa amphibole (Table 3, Analysis 12) have been quoted, would indicate that such properties have been considered typical of kaersutite. Chemically, the Linosa mineral is atypical when compared with other kaersutites, notably because of its relatively high Fe_2O_3/FeO ratio, a feature which prompted Washington to assign it to a distinct species, linosite. It is however akin in its optics and chemistry to an oxyhornblende.

The majority of analyzed kaersutites have $(\gamma - \alpha)$ in the range 0.030–0.032. Variation in the Fe_2O_3/FeO ratios apparently has little effect on the birefringence. However a kaersutite with the abnormally high birefringence of 0.083 ($2V_\alpha = 79–80$; TiO_2 7.55, Fe_2O_3 7.11, FeO 5.05 per cent) has recently been described by Aoki (1959, p. 279). This amphibole occurs as phenocrysts in a scoria. Other kaersutites from the same area with comparable TiO_2 contents but slightly lower degrees of oxidation possess distinctly lower birefringences (Table 3, Analyses 6 and 11).

Irrespective of the contents of TiO_2 or total iron, or degree of oxidation of the iron, a large number of kaersutites have $2V_\alpha = 80 \pm 2°$.

On the assumption that kaersutite is a titaniferous variety of oxyhornblende, many workers appear to have taken an upper limit of 5 per cent TiO_2 for oxyhornblende. Despite Fe_2O_3/FeO ratios close to or greater than unity, many amphiboles designated as oxyhornblende have $(\gamma-\alpha) = 0.019-0.026$ (Table 2), particularly those described by Kunitz (1930). These values do not differ markedly from the birefringence of many green hornblendes. Comparison of oxyhornblendes and kaersutites with comparable degrees of oxidation but differing TiO_2 contents indicates that the birefringence increases slightly with increasing TiO_2.

Not a great deal of optical data on barkevikite is available (Table 4). The birefringence is comparable with many of the oxyhornblendes listed in Table 2. With a higher content of $(FeO+Fe_2O_3)$ and often containing moderate amounts of TiO_2, barkevikite might be expected to possess higher refractive indices than kaersutite. There is need for much more data, which may reveal a distinction from kaersutite based on $2V_\alpha$ (cf. Benson, 1940, p. 289).

It is clear from the data listed in Tables 2–4 that identification of any particular amphibole under discussion cannot be confidently accomplished solely on the over-generalized optical data assigned to these minerals by various workers, since amphiboles referred to these species possess similar ranges of refractive indices, extinction angles and absorption colors. Much more data is necessary in order to define any significance in 2V. The difficulties of optical identification are particularly accentuated by the variation and possible interplay of titania, and degree of iron enrichment and oxidation. The use of low extinction angles as a guide to the degree of oxidation is misleading inasmuch as several kaersutites with low Fe_2O_3/FeO ratios have $\gamma : c$ values less than 10 degrees. It may also be questioned whether the size of $2V_\alpha$ is indicative of the degree of oxidation, inasmuch as certain oxyhornblendes with high $(\gamma-\alpha)$ have $2V_\alpha \sim 80°$.

Engel (1959, p. 974) has recently emphasized the lack of obvious correlations of optics and composition of hornblende, particularly in relation to optical properties/composition diagrams. This point is again emphasized, and here attention may be particularly directed to the limitations of optical properties/composition diagrams showing relationships between various amphibole end-members which themselves are titania-free.

The experimental work of Barnes (1930) demonstrated that the increase in the birefringence depends on the iron content of the amphibole, Fe-free or Fe-poor amphiboles showing little or no increase in $(\gamma-\alpha)$ on heating. Such amphiboles however would be expected to be rare in the normal range of igneous rock compositions. In the formation of an oxyhornblende with comparatively high birefringence, the γ index frequently increases at a greater rate than either the α or β indices. In view of several natural amphiboles with high degrees of oxidation failing to show strong birefringence, it would seem desirable to investigate carefully the products of controlled heating experiments to determine: (i) Whether differing Fe_2O_3/FeO ratios affect the birefringence. (ii) The nature of the structural changes involved in the production of increased birefringence at known temperatures under controlled oxidizing conditions.

Increased birefringence (>0.040) characterizes the oxyhornblendes from Taiwan and Colorado (Table 2, Analyses 9 and 10) and Linosa (Table 3, Analysis 12). These minerals occur in lavas and have high Fe_2O_3/FeO ratios. Parsons (1930, p. 31) has listed an amphibole from Bohemia (TiO_2 5.10, Fe_2O_3 6.96, FeO 2.34 per cent; $\gamma-\alpha=0.042$) whose chemistry and optics conform to the conventional view of an oxyhornblende. The strongly birefringent amphiboles described by Aoki (1959) appear to represent distinctive types inasmuch as they show comparatively little oxidation. Such amphiboles are worthy of more detailed investigation.

In terms of available analyses and detailed descriptions, it is seen that amphiboles conforming both in chemistry and optical properties (particularly high birefringence) to oxyhornblende, are comparatively uncommon. Pending analysis, it would seem desirable to limit the term oxyhornblende to brown calciferous amphiboles with $(\gamma-\alpha)>0.040$ and occurring in lavas. These amphiboles may frequently show strong evidence of magmatic reaction and resorption.

Other brown or reddish-brown amphiboles (particularly those occurring in undersaturated alkaline rocks) with $(\gamma-\alpha)<0.040$, may be conveniently referred to brown hornblendes, unless chemical data results in more precise nomenclature. However, as will be discussed in the occurrence of those minerals, the nature of the parent rock may serve to indicate whether kaersutite or barkevikite is present.

OCCURRENCE

Arising from the results of amphibole heating experiments has been the concept that oxyhornblende (and kaersutite) is not strictly a primary mineral, but is an alteration product of common green hornblende (cf. Hatch, Wells and Wells, 1949, p. 66; Winchell, 1951, p. 439), "probably due to hot gases at a late magmatic stage" (Rogers, 1940, p. 828). In the San Juan lavas, Larsen *et al.* (1937, p. 905) considered that "in considerable part the change from common to basaltic hornblende . . . takes place after eruption and during the crystallization of the groundmass." The latter conclusion is substantiated by chemical and optical data on amphiboles within the one volcanic horizon.

If the term oxyhornblende is to carry with it genetic implications, it is clear that this term should not be used indiscriminately to include brown calciferous amphiboles occurring in intrusive rocks (e.g. many kaersutites) and which have been demonstrated to contain low to moderate Fe_2O_3 contents. Such amphiboles represent normal magmatic crystallization products.

In the case of brown amphiboles possessing comparatively high Fe_2O_3 contents relative to FeO and occurring in intrusive rocks, it is possible that in many cases their composition indicates a response to initially high Fe_2O_3/FeO ratios in the parent melts, crystallizing under conditions of high $[P]H_2O$ or high $[P]O_2$.

Where brown amphiboles with relatively high Fe_2O_3/FeO ratios, but not possessing abnormal birefringences, are present in lavas, then it is likely that oxidation attendant on extrusion has contributed to their chemistry. In lavas where exothermic surface reactions have resulted in temperatures in excess of 750–800° C., a true oxyhornblende may be locally developed. Those lavas in which a calciferous amphibole is a common ferromagnesian constituent and where there is evidence that such temperatures may be attained (Ingerson, 1955) are represented by andesitic and dacitic types.

Under the appropriate physical conditions it is highly likely that any common calcium-sodium amphibole (including kaersutite and barkevikite) may suffer subsequent conversion to a true oxyhornblende. It may be noted that although some kaersutites occurring as cognate xenocrysts in lavas and dyke rocks (Tomita, 1934; Benson, 1940) show varying degrees of resorption and alteration, nevertheless their degree of oxidation and their birefringence are comparable with similar amphiboles present in intrusives. It is inferred that in such cases oxidation took place at only moderate temperatures.

Kaersutite and barkevikite appear to have been recorded dominantly from undersaturated rocks or those members of a differentiation series, in which the principal undersaturated felsic minerals are respectively analcite and nepheline. The latter amphibole has been most frequently noted in nepheline-syenites.

Although the parent rocks vary in composition from highly basic to intermediate, the range of composition of the kaersutites is not very marked, being mainly restricted to limited replacement in the X group of Mg by Fe^{2+}. By contrast, barkevikite reveals a much higher degree of replacement of Mg by Fe^{2+}. This feature, together with a tendency for enrichment in Mn with respect to Fe^{2+} (cf. Goldschmidt, 1954, p. 628), indicates its precipitation at a relatively advanced stage of differentiation, the magma at that time possessing high Fe^{2+}/Mg ratios. The TiO_2-poor amphibole from the Wausau (Wisconsin) quartz-syenite, referred by Weidman (1907, p. 204) to barkevikite, is associated with fayalite and hedenbergite and is thus a member of an iron-enriched assemblage.

In undersaturated rocks the development of analcite rather than the pair albite-nepheline would be facilitated by high water pressures (cf. Turner and Verhoogen, 1960, p. 124). Such hydrous magmatic conditions would not be favorable to any degree of absolute iron enrichment. Where a calciferous amphibole is precipitated in such an environment, it would be expected to show limited replacement of Mg by Fe^{2+} *i.e.* kaersutite would be developed. It is frequently stated that the dark brown amphibole in teschenites is barkevikite, although there appears to be little analytical data to substantiate this claim. It is more likely that the amphibole in question is a kaersutite.

In a nepheline-bearing differentiation series varying in composition from basic to intermediate types, and carrying a brown calciferous amphibole, it is anticipated that a kaersutite would be present in the more basic varieties (*e.g.* the Mount Royal essexites) and that with progressive fractionation, the amphibole would change in its compostion towards a barkevikite. Such a trend is analogous to the trend magnesiohastingsite→ferrohastingsite, proposed by Billings (1928, p. 293), and is similar to the trend in hornblendes from certain calc-alkaline igneous series, *e.g.* the amphiboles from the Southern California bathylith (Larsen and Draisin, 1950, Table III).

The TiO_2-rich environment from which kaersutites have crystallized is illustrated by two examples of co-existing biotites containing 6–8 per cent TiO_2 (Table 3, Analyses 3 and 4). Some confirmation of the differing magmatic conditions under which kaersutite and barkevikite are precipitated may be furnished by a study with a particular differentiation series of the associated opaque oxides. Unfortunately there appears to be little analytical data on the associated opaques.

In rocks with barkevikite, earlier relatively anhydrous conditions would tend to favor the formation early in the differentiation series of a titano-magnetite composed dominantly of a Fe_3O_4-Fe_2TiO_4 solid solution and possessing $(FeO+TiO_2)>Fe_2O_3$. In analcite-bearing rocks with kaersutite, the opaque oxides would tend to be either a TiO_2-poor magnetite with $Fe_2O_3>FeO$, or else a magnetite of the Fe_3O_4-$FeTiO_3$ solid solution type. Concentration of TiO_2 at the stage of kaersutite precipitation would be facilitated by the early separation of a TiO_2-poor magnetite.

Ultimate clarification of many of the proposals in the present discussion obviously must await more detailed studies on possible chemistry/optical properties relationships and response by the amphibole chemistry to varying conditions of differentiation. In particular, a great deal remains to be done concerning the effects of dominant cations (particularly Ti) on optics; in addition, *x*-ray diffraction studies represent a field where considerable information is needed.

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References

Aoki, K. (1959), Petrology of alkali rocks of the Iki Islands and Higashi-matsura District, Japan: *Sci. Rept. Tohoku Univ.*, **6,** Ser. III, 261–310.

Bancroft, J. A. and Howard, W. V. (1923), The essexites of Mount Royal, Montreal: *Trans. Roy. Soc. Canada*, **17,** 13–43.

Barnes, V. E. (1930), Changes in hornblende at about 800° C.: *Am. Mineral.*, **15,** 393–417.

Benson, W. N. (1940), Kaersutite and other brown amphiboles in the Cainozoic igneous rocks of the Dunedin district: *Trans. Roy. Soc. N.Z.*, **69,** 283–308.

Billings, M. P. (1928), The chemistry, optics and genesis of the hastingsite group of amphiboles: *Am. Mineral.*, **13,** 287–296.

Boyd, F. R. (1955), *Ann. Rept. Geophys. Lab. Washington for 1954–55*, 115–119.

Boyd, F. R. (1959), Researches in Geochemistry, ed. P. H. Abelson, 377–396: John Wiley and Sons, N. Y.

Brögger, W. C. (1890), Die Mineralien der Syenitpegmatitgänge der sudnorwegischen Augite- und Nephelinsyenite: *Zeits. Kryst.*, **16,** 412–418.

Campbell, I. and Schenk, E. T. (1950), Camptonite dykes near Boulder Dam, Arizona: *Am. Mineral.*, **35,** 671–692.

Engel, C. G. (1959), Igneous rocks and constituent hornblendes of the Henry Mountains, Utah: *Geol. Soc. Amer. Bull.*, **70,** 951–980.

Goldschmidt, V. M. (1954), Geochemistry: Clarendon Press, Oxford, 730 pp.

Gossner, B. and Spielberger, F. (1929), Chemische und röntgenographische Untersuchungen an Silikaten: *Zeits. Kryst.* **72,** 111–142.

Hallimond, A. F. (1943), On the graphical representation of the calciferous amphiboles: *Am. Mineral.*, **28,** 65–89.

Harada, Z. (1936), Chemische Analysenresultate von Japanischen Mineralien: *J. Fac. Sci. Hokkaido Imp. Univ.*, **3,** Ser. 4, 221–362.

Hatch, F. H., Wells, A. K. and Wells, M. K. (1949), The Petrology of the Igneous Rocks: Thos. Murby and Sons, London, 469 pp.

Ichimura, T. (1931), Notes on brown hornblende and biotite from Shabō-zan, of the Daiton Volcanoes, Taiwan: *Mineral. Mag.*, **22,** 561–568.

Ingerson, E. (1955), Methods and problems of geologic thermometry: *Econ. Geol.*, 50th Ann. Vol., 341–410.

Kawano, T. (1934), Chemical formula of basaltic hornblende: *Proc. Imp. Acad. Jap.*, **10,** 349–352.

Kerr, P. F. (1959), Optical Mineralogy, 3rd Ed.: McGraw-Hill Book Co., N. Y., 442 pp.

Kôzu, S., Yoshiki, B. and Kani, K. (1927), Note on the transformation of common hornblende into basaltic hornblende at 750°C.: *Sci. Rept. Tôhoku Imp. Univ.*, **3,** Ser. III 143–159.

KUNITZ, W. (1930), Die Isomorphieverhältnisse in der Hornblendegruppe: *Neues Jahrb. Mineral.*, **60**, Abt. A, 171–250.

LARSEN, E. S. *et al.* (1937), Petrologic results of a study of the minerals from the Tertiary volcanic rocks of the San Juan region, Colorado: *Am. Mineral.*, **22**, 889–905.

LARSEN, E. S. AND DRAISIN, W. M. (1950), Composition of the minerals in rocks of the Southern California batholith: *Rept. 18th Int. Geol. Cong.*, Pt. II, 66–79.

LINDGREN, W. AND MELVILLE, W. H. (1892), A sodalite-syneite and other rocks from Montana: *Am. J. Sci.*, Ser. 3, **45**, 286–297.

LORENZEN, J. (1884), *Medd. Grønland*, **7**, 27.

MASON, B. (1958), The intrusive rocks of the Kaikoura Mountains, Marlborough, New Zealand: *Trans. Roy Soc. N.Z.*, **85**, 247–262.

MIYASHIRO, A. (1957), The chemistry, optics and genesis of the alkali amphiboles: *J. Fac. Sci. Tokyo Univ.*, **11**, Sect. II, 57–83.

PARSONS, A. L. (1930), A chemical and optical study of amphibole: *Univ. of Toronto, Geol. Ser.* No. **29**, 29–33.

ROGERS, A. F. (1940), Lamprobolite, a new name for basaltic hornblende: *Am. Mineral.*, **25**, 826–828.

SMITH, J. V. (1959), Graphical representation of amphibole compositions: *Am. Mineral.*, **44**, 437–440.

SUNDIUS, N. (1946), The classification of the hornblendes and the solid solution relations in the amphibole group: *Sverig. Geol. Unders.* (*Årsbok*), **40**, No. 4, 1–36.

TOMITA, T. (1934), On kaersutite from Dôgo, Oki Islands, Japan, and its magmatic alteration and absorption: *J. Shanghai Sci. Inst.*, Sect. 2, **1**, 99–136.

TURNER, F. J. AND VERHOOGEN, J. (1960), Igneous and Metamorphic Petrology, 2nd Ed.: McGraw-Hill Book Co. Inc., N. Y., 694 pp.

VENDL, M. (1924), The chemical composition and optical properties of a basaltic hornblende from Hungary: *Mineral. Mag.*, **20**, 227–240.

WASHINGTON, H. S. AND WRIGHT, F. E. (1908). On kaersutite from Linosa and Greenland: *Am. J. Sci.*, **26**, 187–211.

WASHINGTON, H. S. AND MERWIN, H. E. (1922), Augite and hornblende from Kilimanjaro: *Am. Mineral.*, **7**, 121–125.

WEIDMAN, S. (1907), The geology of north central Wisconsin: *Wisc. Geol. Surv. Bull.* **16**, 697 pp.

WILKINSON, J. F. G. (1956), Clinopyroxenes of alkali olivine-basalt magma: *Am. Mineral.*, **41**, 724–743.

WINCHELL, A. N. (1932), Ferrotremolite, oxyhornblende and tourmaline: *Am. Mineral.*, **17**, 472–477.

WINCHELL, A. N. (1945), Variations in composition and properties of the calciferous amphiboles: *Am. Mineral.*, **30**, 27–50.

WINCHELL, A. N. (1951), Elements of Optical Mineralogy, Part II: John Wiley and Sons, N. Y., 551 pp.

YAGI, K. (1953), Petrochemical studies on the alkalic rocks of the Morotu district, Sakhalin: *Geol. Soc. Amer. Bull.*, **64**, 769–810.

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A POORLY CRYSTALLIZED, LOW BARIUM, PSILOMELANE-TYPE MINERAL

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Abstract

A poorly crystallized manganese mineral from Zacatecas, Mexico is described. Its *x*-ray diffraction pattern gives only three distinct lines in addition to a few extremely weak bands and lines. The *x*-ray data indicate the specimen is a psilimelane-type mineral. Chemical analysis shows the mineral to be similar to psilomelane except that barium is low ($BaO = 4.5$ per cent). Significant substitution of potassium, sodium, calcium, and strontium takes place for barium.

The nomenclature of psilomelane and psilomelane-type (Fleischer and Richmond, 1943) is reviewed. It is suggested that the term manganomelane be used as the general name for all hard manganese oxide minerals not specifically identified. Wad should continue to be used for soft manganese minerals not specifically identified.

Introduction

The mineral psilomelane has only recently reached the status of a well defined species. Highlights in this elucidation have been the redefinition of psilomelane as a single species by Vaux (1937), the detailed crystal structure investigation of Wadsley (1952, 1953), and the general review and verification of Fleischer (1960A). These studies have been concerned with well-crystallized psilomelanes which have the formula $(Ba,H_2O)_2Mn_5O_{10}$, or approximate it closely, with $Ba : H_2O$ approximately 1:2, and Mn including Mn^{+4}, Mn^{+2}, as well as various other elements.

This paper is concerned with poorly crystallized psilomelanes and psilomelane-type minerals which have received essentially no recent consideration although they have been recognized by Ramsdell (1932), and others subsequently. One such psilomelane-type mineral is described in detail and it is shown that this particular specimen (1) is very poorly crystallized as determined by its *x*-ray diffraction pattern and (2) has extensive isomorphous substitution of potassium, sodium, calcium, and strontium for barium. Because of these variations from the accepted chemical and structural definition of psilomelane, the term psilomelane-type is used to refer to the specimen being described. Throughout this paper the term psilomelane-type refers to a variant of true psilomelane as defined by Vaux (1937), Wadsley (1952, 1953), and Fleischer (1960A). It is not used in the general sense as suggested by Fleischer and Richmond (1943). Further comment on this terminology is presented below.

Occurrence and Previous Studies

The specimen described in this report is from the La Abundancia mine, Zacatecas, Mexico. This deposit has been most recently described by Wilson and Rocha (1956A); they also give older references. According to

Wilson and Rocha (1956A) the deposit is in the form of mantos and chimneys enclosed in shales and is believed to have formed by replacement by hydrothermal solutions. They also report that by *x*-ray diffraction J. M. Axelrod has identified pyrolusite (dominant mineral), cryptomelane, and two unidentified manganese minerals, as well as quartz, opal, calcite and other gangue minerals. Fleischer (1960B) states that one of Axelrod's unidentified minerals is now recognized to be the so-called "gamma MnO_2"; the other is still unidentified but is not the same as the material described in this paper. The reported presence of pyrochroite by Wilson and Rocha (1956A) was apparently in error according to Fleischer (1960B).

Wilson and Rocha (1956A) note that part of the ore is soft and has been selectively mined, whereas a hard ore has been left in the form of pillars. The mineral described below is undoubtedly an example of the hard ore.

PHYSICAL PROPERTIES

Form = massive, compact
Color = black; Streak = black
Fracture = conchoidal
Hardness = 6
Specific Gravity = 3.98 (at 25° C). Lower than true psilomelane (Fleischer, 1960A); probably due to adsorbed water and isomorphous substitutions for Ba described below.
Luster = Dull, submetallic in hand specimen. Takes excellent polish giving metallic luster in reflected light.

OBSERVATIONS IN REFLECTED LIGHT

The study of several polished sections of the La Abundancia manganese mineral indicates that it is essentially one phase. Several of the sections are homogeneous whereas a few, under high magnification, appear to contain a small number of very minute needles which show some variation in reflectivity upon rotation. Their exact nature could not be determined.

CHEMISTRY

In Table 1 a chemical analysis is presented of the psilomelane-type mineral from the La Abundancia mine. The most noticeable differences between this material and normal psilomelane are its low BaO content and higher than usual contents of CaO, K_2O, and Na_2O; the SrO content is probably normal for psilomelane. Calculations show that if Sr, Ca, K and Na are placed in the (Ba,H_2O) positions, the mineral under discussion fits the chemical requirements of psilomelane. In Table 2 these calculations are summarized and compared with the 14 authenticated psilomelanes described by Fleischer (1960A). For comparison with Fleischer's results, the data are based on $O = 20.00$.

Table 1. Chemical Analysis of Psilomelane-type Mineral, La Abundancia Mine, Zacatecas, Mexico

MnO_2	70.4	Fe_2O_3	2.6
MnO	9.3	MgO	0.9
BaO	4.5	H_2O^+	5.3
SrO	1.4	SiO_2	0.9
CaO	1.6	CO_2	0.3
K_2O	1.5	Others	0.3
Na_2O	0.7	Total	99.7

Notes on Analysis:

1. Wet Analyst: J. A. Greear.
2. Specimen oven dried at 110° C. for 2 hours before analysis. Ignition loss = 1.9%.
3. "Others" are remaining mixed oxides (chiefly Al_2O_3) from ammonium hydroxide precipitate after deduction of Fe_2O_3.
4. Barium and strontium determined by emission spectrographic analysis. Analyst: H. Holt.
5. Traces of Mo, Ni, Cu, Cr detected by *x*-ray fluorescence and emission analysis. Li, W, V, As, Pb, Co and Zn specifically looked for but not detected.
6. A specimen of the analyzed material has been deposited at the U. S. National Museum. U.S.N.M. No. 109398.

For the calculations in Table 2 on the La Abundancia mine specimen, all constituents reported in the analysis (Table 1), with the exception of SiO_2 and CO_2, are considered to be part of the mineral. A required amount of CaO (0.3%) was deducted as CO_2 is present as calcite. As pointed out by Fleischer (1960A), some other constituents, such as

Table 2. Unit Cell Contents of Psilomelanes, 0=20.00

	This Paper La Abundancia	Fleischer (1960A) 14 Psilomelanes
Sum Cations	11.6	11.3 average
Sum Ba Positions	Ba = .30 Sr = .15 K = .33 Na = .22 Ca = .23 1.23	1.26 average
Mn^{+4}	8.43	8.18— 9.00 (range)
Mn^{+2}	1.37	0.90— 1.64 (range)
Mn^{+4}/Mn^{+2}	6.16	5.20—10.00 (range)
H_2O^+	3.07	2.31— 3.09 (range) Average = 2.71
Sum Ba, Sr, Ca, K, $Na+H_2O$	4.30	3.46– 4.51 (range) Average 3.97

Fe_2O_3, may not belong in psilomelane, but no attempt was made to correct for this possibility.

Although the data in Table 2 speak for themselves, there are a few points worth noting.

1. The grouping of Ba, Sr, Ca, K and Na for the purposes of unit cell content calculation in psilomelane is a commonly accepted procedure. For example, it was used by Fleischer (1960A) in his Table 2.
2. The ratio Mn^{+4}/Mn^{+2} for cryptomelane is considerably higher than the largest value (10.00) reported by Fleischer (1960A) for any psilomelane. The specimen under study has a value for the Mn^{+4} Mn^{+2} ratio so low, that no cryptomelane can be expected and, therefore, the K_2O plus Na_2O cannot represent cryptomelane. This is an important point in view of the fact that the psilomelane-type mineral under discussion contains more potassium and sodium ions than it does barium and strontium. (If all the potassium and sodium were allocated to cryptomelane, the specimen would contain about 50 per cent of that species.) Additionally, the analysis yielded significantly more H_2O^+ (5.3 per cent) than can be accounted for in a cryptomelane plus psilomelane mixture of approximately equal proportions.

X-RAY DIFFRACTION

The literature contains several references to poorly crystallized psilomelanes. Ramsdell (1932), in what is probably the first detailed *x*-ray study of specimens called psilomelane, reported a semi-amorphous type along with at least two other types (one of which was true psilomelane, and the other was later described as the new mineral cryptomelane). He suggested that the semi-amorphous type may represent colloidal material as only very few diffuse *x*-ray lines were recorded. Unfortunately, details of Ramsdell's (1932) *x*-ray spacings were not published nor were any chemical data presented to establish the semi-amorphous specimens studied as being true psilomelane chemically (approx. 16 per cent BaO) as defined by Vaux (1937).

Similar difficulties are encountered with other reported occurrences of poorly crystallized psilomelanes. For example, Wilson and Rocha (1956B) mentioned a possible imperfectly crystallized psilomelane from the Talamantes district, Mexico, but they give neither *x*-ray nor chemical data. Fleischér (1960B) states that this specimen is not as well crystallized as most Talamantes specimens (such as Fleischer's, 1960A, specimen number 7) but it shows perhaps three-fourths of the lines on normal exposure. Ramdohr (1956) described a psilomelane from Schneeberg, Saxony, for which he reports only seven *x*-ray diffraction lines. Although this is obviously a poorly crystallized variety no chemical information is given for this psilomelane. (This writer realizes that additional work may show Ramdohr's specimen may not be true psilomelane.) In Fleischer's

TABLE 3. *X*-RAY POWDER DATA FOR LA ABUNDANCIA MINERAL AND SELECTED PSILOMELANES

Psilomelane, Schneeberg Fleischer and Richmond (1943)		La Abundancia Mineral* (This Paper)		Psilomelane, Schneeberg, Ramdohr (1956)	
d (Å)	*I*	*d* (Å)	*I*	*d* (Å)	*I*
4.205	1				
3.825	1				
3.488	8				
3.318	2				
3.217	1				
2.972	1				
2.842	4				
2.663	1				
2.402	8	2.41	6 broad	2.38	m
2.364	1				
2.251	3				
2.191	10	2.19	4 broad	2.16	m
2.138	2				
1.816	5	1.82†	very faint	1.81	s
1.734	2				
1.712	2	1.72†	very faint	1.71	ss
1.636	2	1.62–1.64†	very faint band		
1.562	4	1.57†	very faint band	1.55	s
1.524	1	1.52†			
1.424	4	1.42	10	1.42	m
1.403	6			1.39	s/ss
		1.17	1		

* Filtered iron radiation; camera diameter 143.2 mm.

† Seen only on films of long exposure.

1960A) study of 14 authenticated psilomelanes, we are told that only he identity of the specimens had been proved by *x*-ray diffraction. In ersonal communication Fleischer (1960B) states that all of the 14 silomelanes reported by him (Fleischer, 1960A) give more or less "normal" patterns except number 5 from Manila, Utah, which shows perhaps dozen lines.

Table 3 illustrates the differences between well crystallized and poorly rystallized psilomelanes or psilomelane-type minerals. In Table 3 the -ray powder spacings of the La Abundancia specimen are given. They are compared with those reported by Fleischer and Richmond (1943) for what is considered a well crystallized true psilomelane, as well as the x-ray spacings reported by Ramdohr (1956) from the psilomelane for which there has been no chemical verification. It is important to note that the weak, broad, diffuse bands (1.62–1.64 Å and 1.52–1.57 Å) and faint lines (1.82 and 1.72 Å) of the La Abundancia mineral are seen only on films of long exposure and then sometimes only when specifically looked for. For all practical purposes, the La Abundancia mineral gives only three consistent easily recognizable lines: 2.41, 2.19 and 1.42 Å. Unpublished information received from Fleischer (1960B) reports that x-ray patterns like those from the La Abundancia mineral have been found at the U. S. Geological Survey on minerals from about 20 localities, including quite a few from Cuba. They range from patterns showing only two lines at 2.41 and 2.19 Å to good psilomelane patterns. Qualitative tests showed barium was always present but no complete analyses have been made.

The specimens of Fleischer and Richmond (1943) and Ramdohr (1956) are both from Schneeberg indicating both well crystallized and poorly crystallized examples occur at that locality. The reader is also referred to x-ray powder data on still another specimen from Schneeberg, reported by Gruner (1943), for slight differences in comparison with the Fleischer and Richmond (1943) results. Recently, Mukherjee (1959) has described what appears to be an authentic psilomelane (11–13% BaO) from India for which he has recorded almost twice as many lines as did Fleischer and Richmond (1943) and Gruner (1943).

After being heated to about 550° C. (in air for one hour), the La Abundancia specimen gives an x-ray pattern whose chief constituent is identical to that of hausmannite. Also, a few weak extra lines are present and these most probably represent hollandite; there may also be a trace of bixbyite. Fleischer (1960A) has noted that true psilomelane changes to hollandite at about 550° C. sometimes accompanied by hausmannite or bixbyite. The behavior of the La Abundancia specimen, that is, giving a pattern of hausmannite rather than hollandite, is not surprising in view of its low BaO content. Levinson (1960) has reported that todorokite, which has almost identical contents of MnO, MnO_2, SrO and Fe_2O_3 as the La Abundancia mineral, likewise inverts to give a hausmannite pattern at about 550° C.

Discussion

The unusual manganese mineral here described has been shown to be chemically similar to psilomelane, but with significant isomorphous substitution in the structural position normally occupied by barium. It seems highly unlikely that K, Na, Ca, and Sr are adsorbed in exactly the amounts necessary to fit the chemical requirements of psilomelane. Also, it has been shown that the mineral is poorly crystallized and that its x-ray pattern is closely related to psilomelane. Throughout the study the writer has been particularly attentive to the possibility that some of the unusual aspects of this mineral may be explained by a mixture of two or more minerals. The evidence, however, overwhelmingly favors the conclusion that the specimen is monomineralic.

The study of the La Abundancia mineral has raised many questions. Some of the more interesting might be:

1. Do poorly crystallized psilomelanes or psilomelane-type minerals commonly have considerable isomorphous substitution of K, Na, Ca, and Sr for Ba as does the La Abundancia mineral?
2. Is there a complete series between well crystallized psilomelane and amorphous material (if it exists) of the same or similar composition?

Unfortunately, the answer to these and other questions are not forthcoming from the present study. Many more poorly crystallized psilomelanes and psilomelane-type minerals will have to be studied completely before an attempt to answer these questions is justified. From the evidence and theory presented by Wadsley (1950), it would appear that significant chemical and structural variations can be expected.

NOMENCLATURE

The mineral psilomelane has been clearly defined by Vaux (1937), Wadsley (1952, 1953), and Fleischer (1960A) as a hydrated manganese oxide mineral with approximately 16 per cent BaO, undoubtedly including some SrO. It is unquestionable but that these writers consider psilomelane to be a well crystallized mineral. Accordingly, the specimen from the La Abundancia mine described in this paper cannot be called psilomelane.

The term psilomelane-type has been suggested by Fleischer and Richmond (1943) as a general name for those manganese oxide minerals which are massive, hard, and heavy and not specifically identified. The term is understood to include several distinct minerals, or mixtures, and no chemical formula should be given. Psilomelane-type has in the past, quite within the definition of Fleischer and Richmond (1943), been used for unidentified material with negligible BaO (such as cryptomelane and todorokite).

It is certainly not the desire of this writer to cause confusion in terminology of the psilomelanes as now exists in minerals and synthetic products essentially MnO_2 in composition. However, this paper contains the description of a mineral which shows structural and chemical similarities to true psilomelane; hence, it is called psilomelane-type. Furthermore, by virtue of its poor crystallization as determined by x-ray diffraction, and its low BaO content, the phrases poorly crystallized and low barium have been used in the title of this paper. It must be emphasized that at this time no specific or characteristic formula, or name, is assigned to the mineral described in this paper. It is felt that future work on poorly crystallized psilomelanes and psilomelane-type minerals may find that the La Abundancia specimen is merely a member of a complex chemical and structural mineralogical series.

The reader's attention is called to manganomelane, an infrequently used term, which apparently embodies much of the meaning of psilomelane-type as used by Fleischer and Richmond (1943) and has about 20 years' priority. (Manganomelane was proposed in 1923 by Klockmann, but this writer was not able to obtain the original reference.) Ramdohr (1954) discusses manganomelane briefly, as do others. No less respected authorities than Rankama and Sahama (1950, p. 642) state that manganomelane is a very common mineral. Although the term is currently rather vague in its meaning and extent, perhaps with a modified definition, manganomelane may serve a useful function.

Manganomelane is basically a useful term because it recognizes that all types of structural transitions exist between amorphous material (so-called "wad") and well crystallized specimens called psilomelane, pyrolusite, etc. Further, it recognizes chemical transitions or variations (K, Ba, Pb, etc.), as well as physical variations, from soft "wads" to hard compact materials called psilomelane.

This writer suggests that the definition of manganomelane be modified to be used as a general name for all hard manganese oxide minerals, whether individual minerals or mixtures, not specifically identified. In other words, it would replace psilomelane-type as used by Fleischer and Richmond (1943). It would include: (1) amorphous as well as crystalline specimens and all transitions in between; (2) materials of greatly varying composition; (3) materials of greatly varying physical properties; (4) materials of all environments and conditions of formation—not only of colloidal nature as is required by the original definition. If manganomelane is used in the sense suggested above, it would free the term psilomelane-type to be used for those specimens which are found to have chemical and/or structural characteristics, such as the La Abundancia mineral, similar to true psilomelane. The term wad should continue to be used for soft unidentified manganese oxide minerals. The division between wad and manganomelane, which is based on hardness (sometimes apparent), may be arbitrarily set at H=3.

The point may be raised that wad itself is reported in some standard references with hardness up to H=6 and, therefore, why not use wad to describe all unidentified manganese oxide minerals regardless of hardness? The answer to this is that the term wad, as well as numerous other terms, has been used so loosely in the past that authorities can be found for anything. The use of wad for soft unidentified manganese oxide minerals follows the general usage of the term for the past 50 years, especially in papers on the economic aspects of manganese minerals.

Fleischer (1960B) states he is in favor of the term psilomelane-type (Fleischer and Richmond, 1943) being replaced by manganomelane as the former led to confusion.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation to Dr. E. R. Wright and The Dow Chemical Company for their encouragement and permission to publish this study. I am indebted to my colleague Mr. J. A. Greear for the chemical analysis. Professor E. Wm. Heinrich kindly examined several polished sections. I am grateful to Dr. Michael Fleischer for critically reading this paper and making available unpublished data from the U. S. Geological Survey.

REFERENCES

FLEISCHER, M. (1960A), Studies of the manganese oxide minerals. III. Psilomelane: *Am. Mineral.*, **45,** 176–187.

——— (1960B), Personal communication. Letter dated July 7, 1960.

———, AND RICHMOND, W. E. (1943), The manganese oxides: a preliminary report: *Econ. Geol.*, **38,** 269–286.

GRUNER, J. W. (1943), The chemical relationship of cryptomelane (psilomelane), hollandite, and coronadite: *Am. Mineral.*, **28,** 497–506.

LEVINSON, A. A. (1960), Second occurrence of todorokite: *Am. Mineral.*, **45,** 802–807.

MUKHERJEE, B. (1959), *X*-ray study of psilomelane and cryptomelane: *Mineralog. Mag.*, **32,** 166–171.

RAMDOHR, P. (1954), *Klockmann's Lehrbuch der Mineralogie.* Ferdinand Enke, Stuttgart.

——— (1956), Die Manganerze: Symposium Sobre Yacimientos de Manganeso, **Vol. I.** *XX Congreso Geológico Internac., Mexico,* 19–73.

RAMSDELL, L. S. (1932), An *x*-ray study of psilomelane and wad: *Am. Mineral.*, **17,** 143–149.

RANKAMA, K., AND SAHAMA, T. G. (1950), *Geochemistry.* The University of Chicago Press, Chicago.

VAUX, G. (1937), *X*-ray studies on pyrolusite (including polianite) and psilomelane: *Mineralog. Mag.*, **24,** 521–526.

WADSLEY, A. D. (1950), Synthesis of some hydrated manganese minerals: *Am. Mineral.*, **35,** 485–499.

——— (1952), Role of water in the structure of psilomelane, (Ba, $H_2O)_2Mn_5O_{10}$: *Nature*, **170,** 973–974.

———, (1953), The crystal structure of psilomelane, (Ba, $H_2O)_2Mn_5O_{10}$: *Acta Cryst.*, **6,** 433–438.

WILSON, I. F. AND ROCHA, V. S. (1956A), Manganese deposits of La Abundancia and La Esperanza mines, Zacatecas, Mexico: Symposium Sobre Yacimientos de Manganeso, **Vol. III.** *XX Congreso Geológico Internac., Mexico,* 141–149.

——— (1956B), The Talamantes manganese deposits, Chihuahua, Mexico: *ibid.*. 125–132.

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STABILITY RELATIONS OF IRON AND MANGANESE MINERALS: PHASE EQUILIBRIA AT LIQUIDUS TEMPERATURES IN THE SYSTEM IRON OXIDE-MANGANESE OXIDE-SILICA IN AIR*

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Abstract

The quenching technique has been used to study phase relations in the liquidus temperature region of the system iron oxide-manganese oxide-silica in air, which represents the 0.21 atm. O_2 isobaric section through the quaternary system Fe-Mn-Si-O. The following crystalline phases exist in equilibrium with liquids in the system: Silica (cristobalite or tridymite, depending on temperature), rhodonite ($MnO \cdot SiO_2$), tephroite ($2MnO \cdot SiO_2$), spinel solid solution (approximately Fe_3O_4-Mn_3O_4). Dominant among the primary phase areas are those of silica and spinel, whereas the stability fields of rhodonite and tephroite are restricted to minor areas adjacent to the manganese oxide-silica join. An area comprising mixtures giving rise to two coexisting immiscible liquids occupies a large part of the diagram. Liquidus temperatures in general decrease from the iron oxide-silica join to the manganese oxide-silica join. The lowest liquidus temperature in the system in air is 1205° C. Paths of crystallization of representative mixtures are discussed, with special emphasis on the complications arising because of the presence of a temperature minimum on the liquidus curve of the bounding system iron oxide-manganese oxide.

Introduction

Stability relations among iron silicates have been the subject of many investigations over the last three decades. There has also been considerable interest in manganese silicates during the recent years. In natural occurrences as well as in technologically important systems the oxides and silicates of iron and manganese are commonly closely associated with eath other. Hence a knowledge of phase relations existing among the components iron oxide, manganese oxide and silica is important to petrology, to ore genesis and to research on steelmaking processes.

The present work represents the first step in our attempt to investigate such equilibria. For practical reasons we have chosen to study the system in air. In so doing we are traversing the quaternary system Fe-Mn-Si-O along the 0.21 atm. O_2 isobar at a total pressure of 1 atm. For purpose of simplified illustration this irregularly curved surface may be projected onto a chosen plane, and the resulting diagram has the appearance of a ternary system. Methods of projecting and interpreting such diagrams have been discussed in several previous papers from our laboratories (Muan and Osborn, 1956; Muan, 1957*a*, *b*, 1958; Phillips and Muan, 1959), and their application to the present system will be dealt with in some detail in later sections of this paper.

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Previous Work

The three bounding "binary"* systems have been studied in considerable detail, but no systematic study of the "ternary" system has been reported in the literature. The system iron oxide-silica in air was studied by Darken (1948) and by Muan (1955) as part of more extensive investigations of the system FeO-Fe_2O_3-SiO_2. The diagram shown in Fig. 1 is reproduced from Muan (1957*a*). Phase relations in the system manganese oxide-silica in air were determined recently by Muan (1959), and the diagram is reproduced in Fig. 2. The phase diagram for the system iron oxide-manganese oxide in air is shown in Fig. 3, based on the recent studies by Muan and Sōmiya (in press). Particular attention is

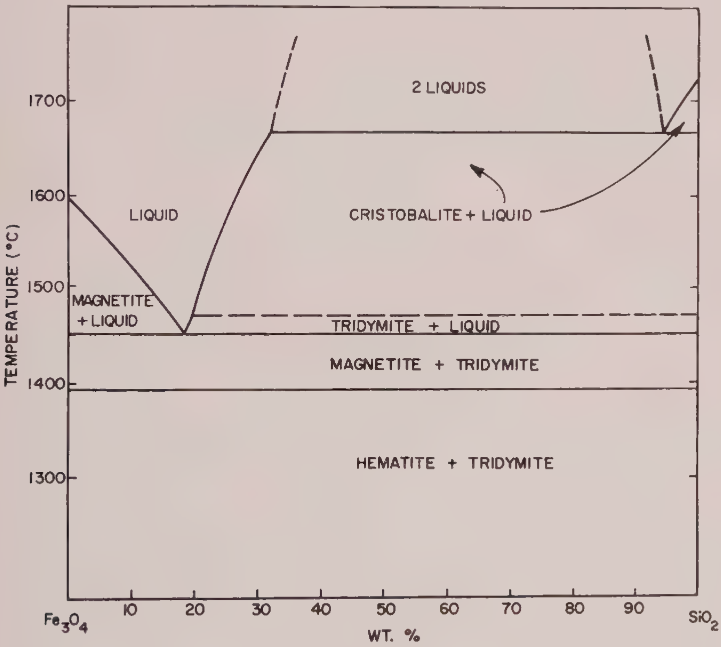

Fig. 1. Diagram showing phase relations in the system iron oxide-SiO_2 in air, after Muan (1955, 1957*a*). The system is not binary, but rather an oxygen isobaric section through the system Fe-Si-O, as explained in the original papers.

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* These systems are not truly binary, but will be referred to as such for sake of simplicity. The term ternary is used with the same limitation throughout this paper.

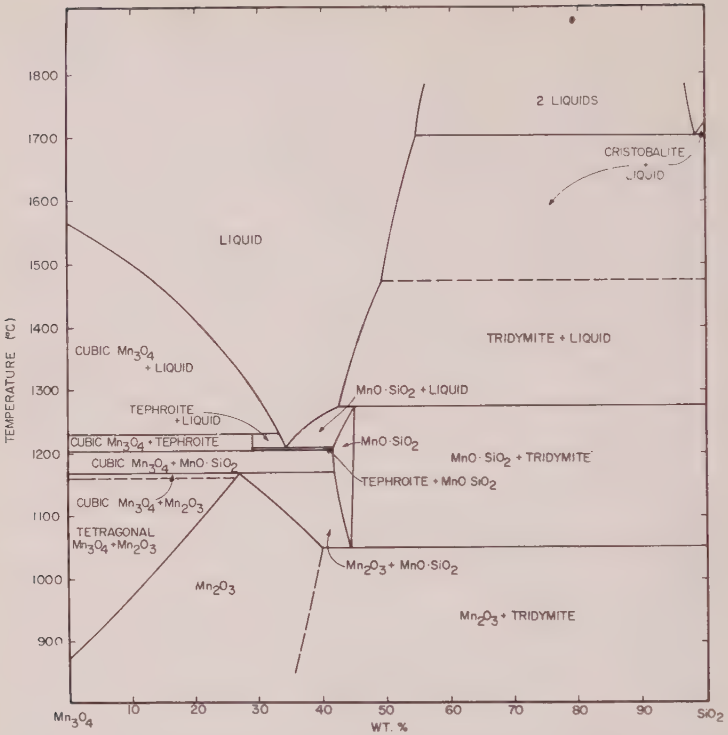

FIG. 2. Diagram illustrating phase relations in the system manganese oxide-SiO_2 in air after Muan (1959). The system is not binary, but rather an oxygen isobaric section through the system Mn-Si-O, as explained in the original paper.

called to the temperature minimum on the liquidus curve and the stabilization of the spinel structure of magnetite relative to the hexagonal structure of hematite as manganese oxide is added to iron oxide.

EXPERIMENTAL METHOD

General Procedure

The quenching technique was used in this investigation. Starting materials made up from pure oxides were held in platinum containers at selected temperatures in air until equilibrium was established among gas and condensed phases. The samples were then quenched rapidly to room temperature and the phases present determined by microscopic and *x*-ray examination.

Starting Materials

Reagent grade chemicals served as starting materials. The source of silica was "Baker Analyzed" silicic acid, which was dehydrated by ignition at 1200° C. for 24 hours. The iron oxide used was "Baker Analyzed"

Fe_2O_3 which was dried by heating at 400° C. for 12 hours, and the manganese oxide used was "Baker Analyzed" MnO_2.

After grinding and mixing these materials in required proportions, each mixture was preheated at suitable temperatures to slowly decompose the starting oxides to those stable at high temperatures. This process had to be carried out with utmost caution because the higher oxides of manganese (notably MnO_2, also Mn_2O_3) give off oxygen violently with the result that material may be lost by splashing of the melts. The temperature of the final heating step was in most cases above the liquidus, and the melt thus obtained, after cooling to room temperature, consisted of glass or a heterogeneous product with small quench crystals scattered over the entire mass.

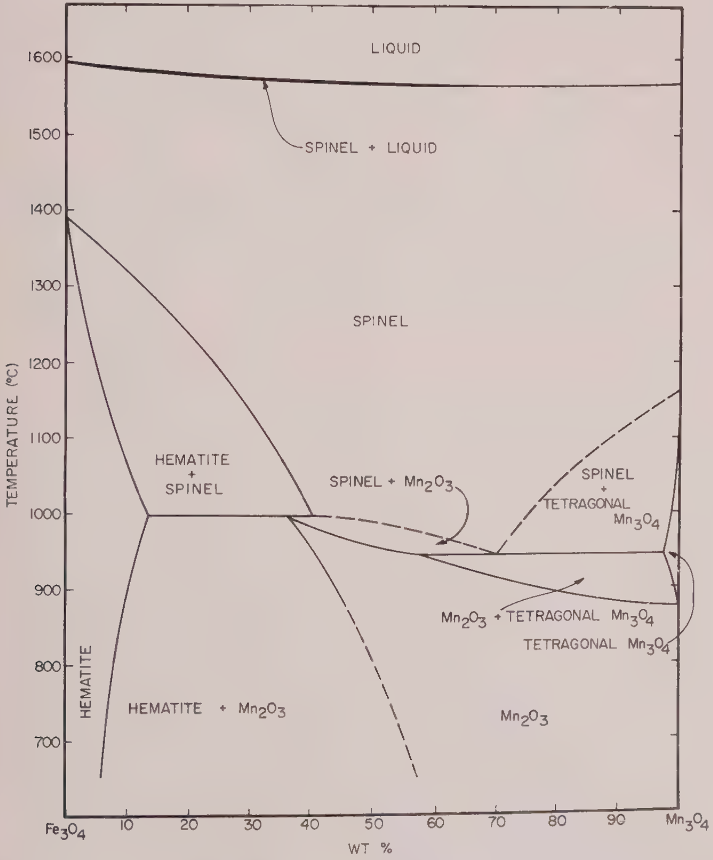

FIG. 3. Diagram showing phase relations in the system iron oxide-manganese oxide, after Muan and Sōmiya (in press). The system is not binary, but rather an oxygen isobaric section through the system Fe-Mn-O, as explained in the original paper.

Furnaces and Temperature Control

Most of the quench runs were carried out in vertical tube furnaces with resistance windings of platinum or an 80% platinum—20% rhodium alloy. Constancy of temperature in these furnaces was maintained by commercial electronic equipment activated through a thermocouple (platinum—90% platinum 10% rhodium) inserted close to the hot spot of the furnace. Actual temperatures were read with a platinum –90% platinum 10% rhodium thermocouple calibrated against known melting points defined as follows: Gold (Au), 1063° C.; diopside ($CaMgSi_2O_6$), 1391.5° C.; pseudowollastonite ($CaSiO_3$), 1544° C. Quench runs at temperatures above 1515° C. were carried out in a gas-air-oxygen combustion furnace in which air atmosphere was maintained around the sample by means of a zirconia protection tube separating the sample from the combustion chamber. Temperatures in this furnace were measured with an optical pyrometer calibrated at the following fixed points: Melting point of pseudowollastonite, 1544° C.; lower limit of formation of two liquids in a 90% SiO_2-10% CaO mixture, 1707° C.; melting point of platinum, 1769° C.

Temperatures reported in the present paper are according to the Geophysical Laboratory Scale up to 1550° C., and according to the 1948 International Scale at higher temperatures. Correction factors for converting temperatures from one of these scales to the other are found in a paper by Sosman (1952). Below 1550° C. the two scales are almost identical.

Examination of Quenched Samples

The phases present in quenched samples were determined mainly by microscopic examination. Both transmitted as well as reflected light techniques were used. The former technique was useful for identification of SiO_2 (tridymite or cristobalite) and manganese silicates, whereas the latter was far superior for identification of the spinel phase. Also, the reflected light examination of polished sections was found to be much more reliable for distinguishing primary crystals grown in equilibrium with liquids at high temperatures from those formed during quenching of the liquids. The former crystals not only are larger, but in addition they show sharp outlines as distinguished from the irregular dentritic shapes of the quench crystals.

The identity of crystalline phases was further confirmed by *x*-ray investigation, using either a Norelco or a GE-XRD-3 spectrometer unit with iron radiation. The *x*-ray technique was also used to determine compositions of the spinel solid solution crystals appearing in equilibrium with liquids. The GE-XRD-3 unit was used for this purpose. The machine was run at a scanning rate of 1/5° 2 θ per minute, and NaCl was used as an internal standard.

Results

Results of significant quench runs are illustrated graphically in Fig. 4.* The diagram presented in this figure is a simplified representation of phase relations along the 0.21 atm. O_2 isobar through the quaternary system Fe-Mn-Si-O. A quaternary system is usually represented by a regular tetrahedron, and the isobaric situation referred to above corresponds geometrically to an irregularly curved surface traversing the tetrahedron. The diagram presented in Fig. 4 is obtained by projecting points from the irregularly curved surface onto the plane Fe_3O_4-Mn_3O_4-

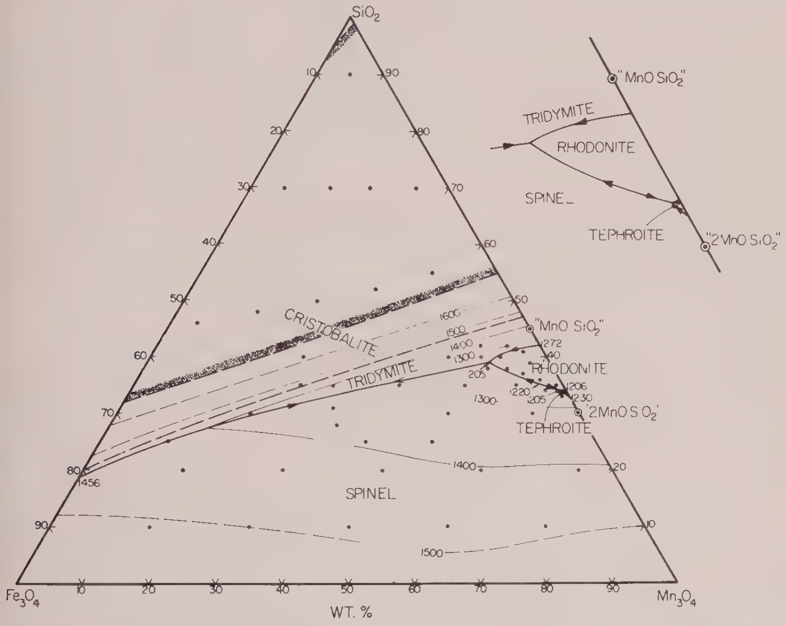

FIG. 4. Diagram illustrating phase relations at liquidus temperatures in the system iron oxide-manganese oxide-silica in air, based on data obtained in the present investigation. Heavy lines are boundary curves, with arrows pointing in directions of decreasing temperatures, lines with stippling on one side indicate limits of two liquid region, and light lines are liquidus isotherms. Dash lines are used in regions of the diagram where data are sporadic or lacking. Dots represent compositions of mixtures studied.

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* The detailed results of the significant quench runs are available from the American Documentation Institute, Auxiliary Publications Project, c/o Library of Congress, Washington 25, D. C.; Document No. 6627; Price $1.25 for photoprints or 35 mm. microfilm. Advance payment is required, made out to Chief, Photoduplication Service, Library of Congress.

SiO_2. The triangular diagram thus obtained has the appearance of a ternary system, and can also be treated like a ternary system as far as path of crystallization is concerned. However, it is important to keep in mind that isobaric invariant points in the triangular diagram in reality are intersections between the O_2 isobaric surface ($P_{O_2} = 0.21$ atm.) and quaternary univariant lines. (Compare a previous paper from our laboratories, Muan 1958).

The most significant features of the phase relations are as follows: The crystalline phases occurring in equilibrium with liquids in the system are silica (tridymite or cristobalite, depending on temperature), rhodonite, tephroite and spinel solid solution. The first and the last of these phases (silica and spinel) together occupy approximately 99% of the composition area, whereas the fields of rhodonite and tephroite are restricted to minor areas adjacent to the manganese oxide-silica join. The field of tephroite in particular is very small, as only traces of iron oxide make the orthosilicate phase unstable in air. Liquidus temperatures decrease rapidly from the high temperature plateau (~1700° C.) characterizing the part of the system where two immiscible liquids coexist in equilibrium, to the 1200–1450° C. range along the tridymite-spinel boundary curve. Temperatures along the latter decrease in the direction from the iron oxide-silica join toward the manganese oxide-silica join. The lowest liquidus temperature is 1205° C. The liquidus curve in the system iron oxide-manganese oxide in air has a temperature minimum which gives rise to a trough extending part way into the "ternary" system as SiO_2 is added. This trough "dies out" before reaching any of the boundary curves in the "ternary" system, and hence no temperature minima are present along these curves.

There are two isobaric invariant situations in the system, characterized by the following phase assemblages: At 1205° C. and an O_2 pressure of the gas phase of 0.21 atm. tridymite, rhodonite, spinel and liquid of composition 9 wt.% Fe_3O_4, 52 wt.% Mn_3O_4, 39 wt.% SiO_2* coexist in equilibrium. Also at 1205° C. and the same O_2 partial pressure rhodonite, tephroite, spinel and liquid of composition <0.5 wt.% Fe_3O_4, ~ 45.5 wt.% Mn_3O_4 and ~ 54 wt.% SiO_2 are present together in stable equilibrium.

Of the crystalline phases occurring in the system, silica (tridymite or cristobalite) is a pure phase corresponding to the chemical formula SiO_2. Rhodonite has a slight variation in MnO SiO_2 ratio (compare Fig. 2) and probably takes some iron oxide (ferrosillite) into solid solution. Tephroite probably also contains some iron oxide (fayalite) in solid solution. These two phases are represented in a simplified manner by the composition points $MnO \cdot SiO_2$ and $2MnO \cdot SiO_2$, respectively, in the diagrams. Magnetite (Fe_3O_4) and the cubic form of hausmannite (Mn_3O_4) form a continuous solid solution series (spinel) at high temperatures (compare Fig. 3).

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* Total iron oxide expressed as Fe_3O_4 and total manganese oxide expressed as Mn_3O_4.

In order to illustrate relation of compositions of spinel and liquid phases coexisting in equilibrium, a diagram of fractionation curves is shown in Fig. 5. Fractionation curves are constructed from conjugation lines in such a way that the latter are tangent to the former. (A conjugation line is a straight line connecting points representing compositions of two coexisting phases.) The diagram in Fig. 5 is a simplified drawing inasmuch as it illustrates projections onto the plane Fe_3O_4-Mn_3O_4-SiO_2 of fractionation curves traversing the tetrahedron representing the system Fe-Mn-Si-O.

DISCUSSION

We will focus our attention in the following on the courses of crystallization of mixtures where spinel is one of the phases present. These

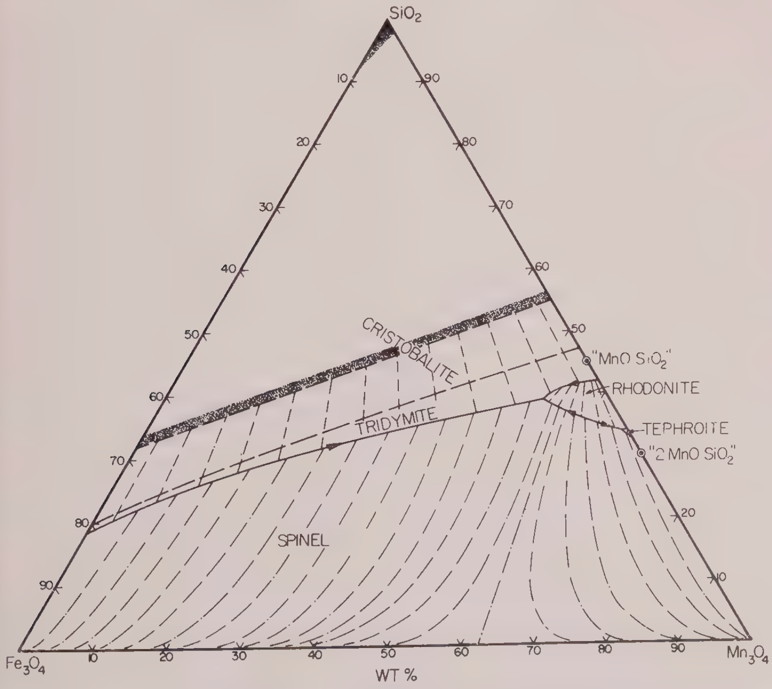

FIG. 5. Diagram illustrating as medium dash-dot lines fractionation curves in the system iron oxide-manganese oxide-silica in air. Other line symbols used have the same meanings as explained in legend to Fig. 4.

relations will be discussed by choosing specific compositions as examples to show the principles involved.

Two limiting types of crystallization are generally recognized, fractional crystallization and equilibrium crystallization. The former term refers to a crystallization taking place under conditions such that no reaction takes place between the crystals formed at any instant during crystallization and the liquid with which they are in contact. In this case the crystallization path follows the fractionation curves until a boundary curve is reached. From there on the liquid composition usually changes along the boundary curve, and the last trace of liquid disappears only after an invariant point has been reached. Hence, in the present system liquid under this type of crystallization will disappear at the temperature of one of the isobaric invariant situations at 1205° C. (see Fig. 4) or at the maximum (1220° C.) on the rhodonite-spinel boundary curve.

Somewhat more complicated is the derivation of paths of crystallization under equilibrium conditions, that is when the liquid during the crystallization process reacts with the crystals to make the composition of all crystals uniform at any instant. This equilibrium path can be derived by methods described particularly well in several contributions by members of the Staff of the Geophysical Laboratory of the Carnegie Institution of Washington. (See for instance papers by Bowen and Schairer, 1935, and by Osborn and Schairer, 1941.) The application of these principles to systems in which changes in oxidation states take place, such as in the present case, has been discussed in papers from our laboratories. (See for instance a paper in 1958 by Muan.)

Examples of paths of equilibrium crystallization are given in Figs. 6–8. Consider first mixture *A* in Fig. 6. Spinel crystals start separating out at approximately 1530° C., the first crystals having the composition a'. Upon further cooling, more crystals of spinel with composition changing from a' to a'' separate out, and the liquid composition changes along the curved path (heavy solid line) from *A* to a_2. At the latter point the liquid has become saturated with SiO_2, and tridymite and spinel crystallize together as the liquid composition changes along the boundary curve from a_2 to a_3 and the spinel composition changes from a'' to a'''. The last trace of liquid disappears at the temperature corresponding to point a_3, approximately 1340° C., leaving as end product a mixture of tridymite and spinel, the former of composition SiO_2, the latter of uniform composition a'''.

Mixtures *B*, *C* and *D* behave similarly, the final product of crystallization in all cases being the same as in mixture *A*. However, the early stages of crystallization differ, depending on the composition of the original mixture. Mixture *B* consists of one homogeneous liquid above 1600° C. At the latter temperature silica starts separating out, and the liquid composition changes along the extension of the straight line from the SiO_2 corner through point *B*. As the liquid composition reaches point b_1, spinel crystals of composition b' start separating out, and as more heat is withdrawn from the system, silica and spinel of continuously changing composition (b'-a''') crystallize out together. The behavior of mixture *C* is slightly different in that two immiscible liquid phases (c_1 and c_2) coexist in equilibrium slightly above liquidus temperature. The first crystalline phase to appear is silica (cristobalite), and as this crystallizes out the composition of liquid c_1 changes toward c_3 and that of c_2 toward c_4, and the relative amount of the latter decreases toward zero. As more

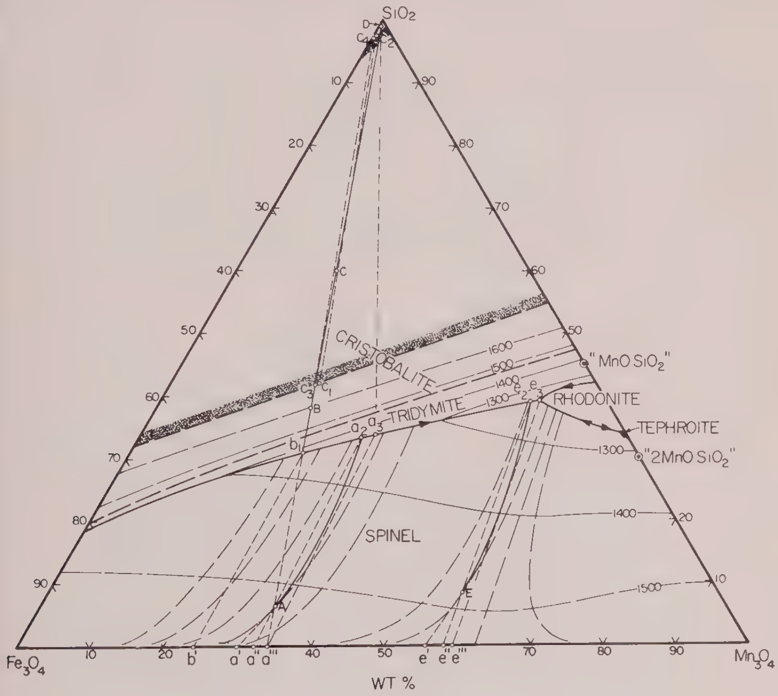

FIG. 6. Diagram showing paths of equilibrium crystallization of selected mixtures in the system iron oxide-manganese oxide-silica in air. In addition to boundary curves and liquidus isotherms shown in Fig. 4, the following line symbols are used in the present diagram: Medium dash-dot lines are fractionation curves, heavy solid lines paths of equilibrium crystallization, light lines liquidus isotherms, and lines with stippling on one side are limits of two-liquid region. Open circles with accompanying letters refer to mixtures and compositions of phases as discussed in the text. Light straight dash lines are conjugation lines connecting points representing compositions of phases coexisting in equilibrium.

heat is withdrawn from the system, silica continues to crystallize from a homogeneous liquid, and the further path of crystallization is analogous to that of mixture *B*. Mixture *D* behaves almost identically to *C* except that first a homogeneous liquid phase is present above liquidus temperature, this is followed by a temperature range of stable existence of cristobalite and one liquid phase, then a temperature range of coexistence of cristobalite and two liquids. From the latter point on, the crystallization path is identical to that of *C*.

The following sequence of phase changes is observed in mixture *E* during equilibrium crystallization: Spinel crystals of composition changing from e' to e'' separate out between approximately 1480 and 1215° C., with liquid composition changing along the curved path (heavy solid line) from *E* to e_2. With silica (tridymite) and spinel crystallizing together, the liquid composition changes along the boundary curve from e_2 to e_3 until at the temperature of the latter (approximately 1205° C.) rhodonite separates out together with the other crystalline phases and the liquid disappears completely.

It will be noticed that in all mixtures chosen as examples so far the iron oxide/manganese oxide ratio of the spinel phase decreases as the equilibrium crystallization process proceeds with decreasing temperature. This is not the case with all mixtures in the system iron oxide-manganese oxide-silica in air, as is demonstrated in Fig. 7, showing the composition area adjacent to the manganese oxide apex of the triangle representing the system. There are three straight lines which are particularly important for purposes of classifying crystallization phenomena in this area. The first of these is the conjugation line joining the composition of the liquid at the isobaric invariant point e_3 with point e''' (compare Fig. 6) representing composition of the spinel phase in equilibrium with that liquid. The second is the straight fractionation curve g_2-g'' (compare Fig. 5) separating those with a convex curvature to the right from those with a convex curvature to the left. The third is the extension (k_2-k'') of the line joining the $MnO \cdot SiO_2$ composition point with the maximum on the rhodonite-spinel boundary curve. This maximum is determined as the point on the boundary curve for which the liquid-spinel conjugation line (the tangent to the fractionation curve) points toward the $MnO \cdot SiO_2$ composition point. Mixtures *F*, *G*, *H*, *K*, *M* in Fig. 6 are located to the left of line g_2-g'', on line g_2-g'', between lines g_2-g'' and k_2-k'', on line k_2-k'', and to the right of line k_2-k'', respectively, in that order. During equilibrium crystallization of these mixtures the liquid compositions follow paths which can be derived from fractionation curves by methods analogous to those used in connection with Fig. 6. For the present discussion we are mainly concerned with the direction of change of iron oxide/manganese oxide ratios of the spinel phase as temperature decreases and crystallization progresses. In mixture *F* this ratio first decreases from f' to f'' as the liquid composition changes along the curved path (heavy solid curve) from *F* to f_2, and then increases from f'' to f''' as the liquid composition changes along the rhodonite-spinel boundary curve from f_2 to f_3. The same type of reversal of change of iron oxide/manganese oxide ratio of the spinel phase is encountered in all mixtures in the spinel primary field between lines e_3-e''' and g_2-g''.

Mixture *G* is located on line g_2-g''. In this case the straight line g_2-g'' not only is the fractionation curve but also the first part of the path of crystallization. As the liquid composition changes along this line the iron oxide/manganese oxide ratio of the spinel phase remains constant (g''), and only as the liquid composition later changes along the rhodonite-spinel boundary curve from g_2 to g_3 does the iron oxide/manganese oxide ratio of the spinel phase change (from g'' to g''').

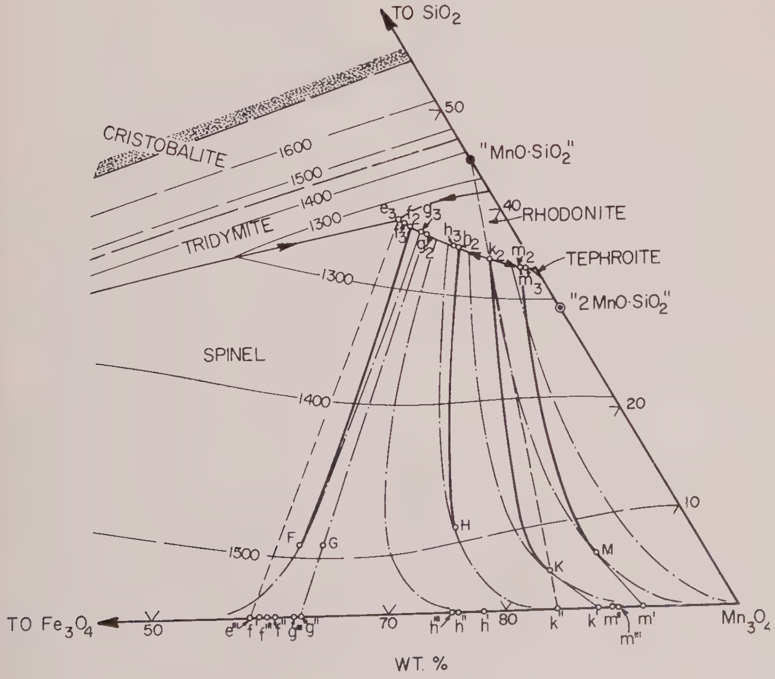

FIG. 7. Diagram illustrating paths of equilibrium crystallization of selected mixtures located in the spinel field in manganese oxide rich part of the system iron oxide-manganese oxide-silica in air. Line symbols used have the same meanings as explained in legend to Fig. 6.

In mixture H, located between lines g_2-g'' and k_2-k'', the iron oxide/manganese oxide ratio of the spinel phase increases continuously during the crystallization process, first from h' to h'' as the liquid composition changes along the heavy solid line from H to h_2, and subsequently from h'' to h''' as the liquid composition changes along the rhodonite-spinel boundary curve from h_2 to h_3.

Mixture K is located on line k_2-k''. As crystallization proceeds under equilibrium conditions in this mixture the iron oxide manganese oxide ratio of the spinel phase increases from k' to k'' as the liquid composition changes along the curved path (heavy solid line) from K to k_2. As the latter point is reached, the liquid phase disappears, and iron oxide manganese oxide ratio of the spinel remains constant.

Mixture M is located on the right side of line k_2-k'', and a reversal in the direction of change of composition of the spinel phase takes place during the crystallization. The iron oxide manganese oxide ratio first increases from m' to m'' as the liquid composition changes from M to m_2, and then decreases from m'' to m''' as the liquid composition changes from m_2 to m_3.

A couple of examples of paths of crystallization involving liquids in the field of rhodonite will be discussed, because of the complications arising from the incongruent melting of this compound. The relations are illustrated in Fig. 8.

The behavior of mixture N is very simple. Tridymite starts separating out at approximately 1400° C., and the liquid composition changes along the straight line N-n_2. At the latter point rhodonite starts separating out, and tridymite and rhodonite coexist in equilibrium with a liquid changing composition along the boundary curve from n_2 to n_3. At the temperature of the latter, approximately 1205° C., the liquid phase disappears, leaving as end product a mixture of tridymite, rhodonite and spinel.

The sequence of phase changes taking place during equilibrium crystallization of mixture P is more complicated. As tridymite starts to crystallize out at approximately 1300° C. the liquid composition changes along the straight line from P to p_2. At p_2 rhodonite starts to crystallize and tridymite to dissolve, and the liquid composition changes along the tridymite-rhodonite boundary curve from p_2 to p_3. At the latter point the last trace of tridymite has disappeared, and with rhodonite as the only crystalline phase present the liquid composition changes along the straight line from p_3 to p_4. Spinel (composition p'''') starts to separate out together with rhodonite at the temperature corresponding to p_4, and the liquid composition now changes along the rhodonite-spinel boundary curve from p_4 to n_3. At the temperature of the latter point,

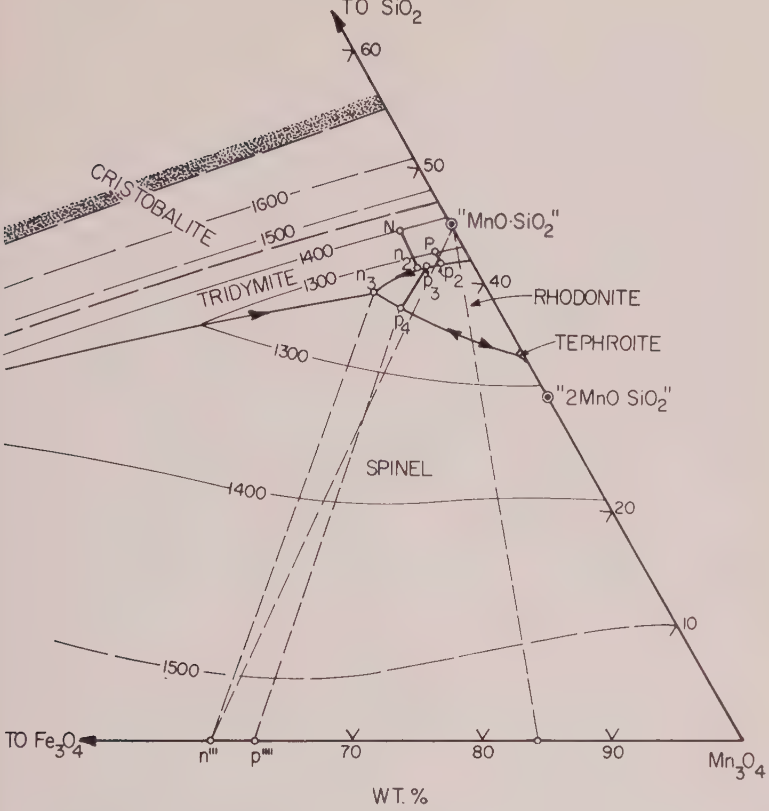

Fig. 8. Diagram illustrating paths of crystallization of selected mixtures in vicinity of rhodonite field in the system iron oxide-manganese oxide-silica in air. Line symbols used have the same meanings as explained in legend to Fig. 6.

approximately 1205° C., tridymite again makes its appearance in the phase assemblage as the liquid disappears, and the end product is a mixture of tridymite, rhodonite and spinel.

Acknowledgments

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References

Bowen, N. L., and Schairer, J. F. (1935), The system $MgO\text{-}FeO\text{-}SiO_2$: *Am. J. Sc.* (5th Series), **29**, 151–217.

Darken, L. S. (1948), Melting points of iron oxides on silica; phase equilibria in the system Fe-Si-O as a function of gas composition and temperature: *J. Am. Chem. Soc.*, **70,** 2046–2053.

Muan, A. (1955), Phase equilibria in the system FeO-Fe_2O_3-SiO_2: *J. Metals*, **7**, September 1955; *Trans. Am. Inst. Mining Met. Engrs.*, **203,** 965–976.

Muan, A., and Osborn, E. F. (1956), Phase equilibria at liquidus temperatures in the system MgO-FeO-Fe_2O_3-SiO_2: *J. Am. Ceram. Soc.*, **39,** 121–140.

Muan, A. (1957*a*), Phase equilibria at liquidus temperatures in the system iron oxide-Al_2O_3-SiO_2 in air atmosphere: *J. Am. Ceram. Soc.*, **40,** 121–133.

Muan, A. (1957*b*), Phase equilibrium relationships at liquidus temperatures in the system FeO-Fe_2O_3-Al_2O_3-SiO_2: *J. Am. Ceram. Soc.*, **40,** 420–431.

Muan, A. (1958), Phase equilibria at high temperatures in oxide systems involving changes in oxidation states: *Am. J. Sc.*, **256,** 171–207.

Muan, A. (1959), Phase equilibria in the system manganese oxide-SiO_2 in air: *Am. J. Sc.*, **257,** 297–315.

Muan, A., and Sōmiya, S. (in press), The system iron oxide-manganese oxide in air: *Am. J. Sc.*

Osborn, E. F., and Schairer, J. F. (1941), The ternary system pseudowollastonite-akermanite-gehlenite: *Am. J. Sc.*, **230,** 715–763.

Phillips, B., and Muan, A. (1959), Phase equilibria in the system CaO-iron oxide-SiO_2 in air: *J. Am. Ceram. Soc.*, **42,** 413–423.

Sosman, R. B. (1952), Temperature scales and silicate research: *Am. J. Sc.*, *Bowen Volume, Part* **2**, 517–528.

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NEIGHBORITE, $NaMgF_3$, A NEW MINERAL FROM THE GREEN RIVER FORMATION, SOUTH OURAY, UTAH*

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Abstract

Neighborite, $NaMgF_3$, occurs in the dolomitic oil shale of the Eocene Green River formation of South Ouray, Uintah County, Utah. It is associated with dolomite and quartz, and the accessory minerals burbankite, nahcolite, barytocalcite, garrelsite, wurtzite, calcite, and pyrite. The mineral occurs in pink rounded grains or in clear twinned octahedral crystals 0.1 to 0.5 mm. in diameter. It has a vitreous luster, uneven fracture, a hardness of 4.5, and is insoluble in water. The specific gravity is 3.03 (measured) and 3.06 (calculated). Neighborite is optically anisotropic with very low birefringence and a mean index of refraction 1.364. The crystals are invariably complexly twinned.

X-ray powder patterns show that neighborite is isostructural with perovskite, $CaTiO_3$. The pattern was indexed on an orthorhombic unit cell having a probable space group *Pcmn*, with dimensions $a=5.363$ Å, $b=7.676$ Å and $c=5.503$ Å. The expansion of the unit cell was followed to 954° C. using a heating stage on the diffractometer. At 760° C. the orthorhombic a and c axes coalesce and from 760° to 900° C. the cell is tetragonal or pseudotetragonal with $a=3.942$ Å and $c=3.933$ Å (at 760° C.). At 900° ±25° C. the unit cell becomes cubic with $a=3.955$ Å. The crystal structure of neighborite is interpreted in terms of the known structure of perovskite.

Introduction

In an extended study of the mineralogy of the Green River formation of Utah and Wyoming, one of the minerals found in the dolomitic oil shale proved to be a sodium magnesium fluoride, previously undescribed as a mineral. Its x-ray powder diffraction pattern immediately showed that it belongs to the perovskite family of crystal structures of formula type ABX_3. The present study substantiates the suggestion made by Ludekens and Welch (1952) that $NaMgF_3$ is among a group of fluorides whose structures appear to belong to the various modifications of the perovskite type. The significance of the mineral was further enhanced when it became apparent that its structure is closely analogous in detail to that of perovskite itself. In this paper the occurrence, physical properties, crystallography and thermal properties of the new mineral are described. The mineral is named "neighborite" in grateful acknowledgment of the continued friendly interest and helpfulness of Mr. Frank Neighbor, District Geologist of the Sun Oil Co. at Salt Lake City. Through Mr. Neighbor's efforts the specimens of South Ouray and Sun-Havenstrite well cores and cuttings were preserved and made available to us, thus making possible the discovery of not only neighborite but also the new mineral garrelsite with elpidite and burbankite in the Utah Green River formation.

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* Publication authorized by the Director, U. S. Geological Survey.

We wish to express our thanks to three of our colleagues: Blair Jones for his help in the synthesis of neighborite, Nola B. Sheffey for the spectrographic analysis, and Daniel E. Appleman for the calculated *d*-spacings of neighborite obtained with the Burroughs 220 calculator.

GEOLOGIC OCCURRENCE

Neighborite was first found as clusters of pink and brown rounded grains in a dark brown to grayish black dolomitic oil shale of the Green River formation of South Ouray, Utah. It is associated with burbankite, nahcolite, wurtzite, barytocalcite, garrelsite, pyrite, calcite, and quartz. Cores from the South Ouray well at an unknown depth but somewhere between 1700 and 2300 feet consist of layers of fine-grained dark brown to black dolomitic oil shale interbedded with layers of coarsely crystalline material of barytocalcite and nahcolite. Most of the crystals of neighborite which occur at the top of the fine-grained shale layer are rounded to subrounded as shown in Fig. 1. This fine-grained shale layer, as shown by its *x*-ray powder pattern, consists essentially of dolomite and quartz with a minor trace of feldspar. Some rounded neighborite occurs in discrete grains as inclusions in crystals of barytocalcite in the coarsely crystalline layers.

Neighborite also occurs as cream-colored or clear, colorless octahedral crystals (Fig. 2). Such crystals were obtained from the well cuttings of the Sun Havenstrite well of Uintah County, Utah, at various depths. The crystals used in this study occur in cuttings that were collected from a depth of approximately 1930 feet within an interval of 10 feet. Besides fragments of oil-bearing dolomitic shale, the cuttings contain barytocalcite and pyrite. The total amount of neighborite obtained is less than thirty milligrams.

The mineral has so far been found only from these two wells in Utah, which are located less than a mile apart in an area about 5 miles SSE of South Ouray, Uintah County, Utah. Cryolite, Na_3AlF_6, has been found in the oil shales of the Green River formation from Colorado. The dolomitic oil shale there contains dawsonite, $NaAl(CO_3)(OH)_2$, and nahcolite.

PHYSICAL AND OPTICAL PROPERTIES

Neighborite has a vitreous luster, an uneven fracture, no distinct cleavage, and a hardness of 4.5. Neighborite is insoluble in water but slowly soluble in hydrochloric or nitric acid and more rapidly in sulfuric acid. The specific gravity of neighborite was determined both by the

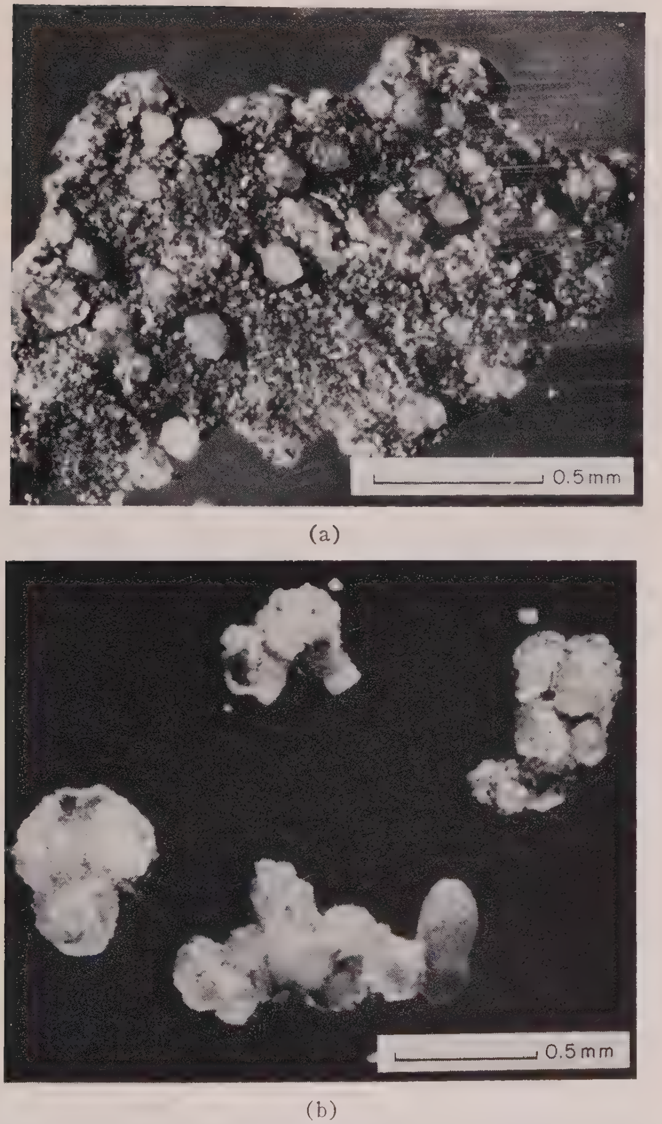

FIG. 1. Typical habit of neighborite crystals: (a) rounded crystals on a thin layer of dolomitic oil shale; (b) loose clusters of rounded and oblong crystals.

suspension or sink and float method using methylene iodide-bromoform mixtures, and with the Berman precision microbalance. Under a binocular microscope, a 0.3-mm. diameter grain was observed to be suspended within the liquid column in a nearly stationary position for five to ten minutes. The specific gravity of neighborite determined in this way is 3.02. In another test, a sample of 4.90 mg. of the best hand-picked octahedral crystals of neighborite was used for determination of its specific gravity with the Berman balance. The specific gravity so measured is 3.03±0.03.

Optically, the crystals are measurably anisotropic, but show very low birefringence about 0.003. The mean index of refraction measured with sodium light at 25° C. is 1.364±0.002. The crystals invariably show complex ill-defined polysynthetic twinning and consequently the optical properties cannot be determined completely.

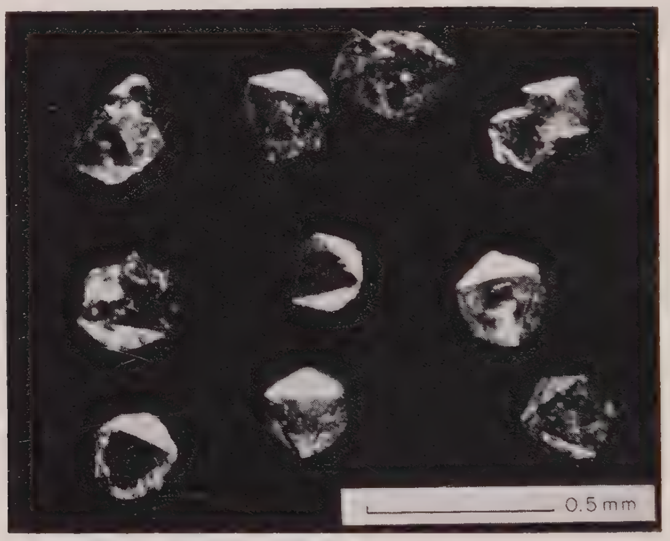

FIG. 2. Clear, single and interpenetrating crystals of neighborite.

The octahedral crystals often show, in addition to the complex microscopic twinning, apparent interpenetration twinning. Besides the octahedral forms {111} the crystals show small cube faces {100} which truncate the octahedral faces. The fact that all of the crystals studied are multiply twinned was shown by the single crystal *x*-ray studies.

CHEMICAL COMPOSITION AND SYNTHESIS

Because of the small amount of clean sample at our disposal, a complete chemical analysis of the mineral was not possible. One small sample weighing several milligrams was submitted for spectrographic analysis. The semiquantitative analysis of the mineral shows major amounts of Na, Mg, F, and Si. The results of the minor elements are shown in Table 1. The silica shown in the analysis is due to the small amounts of quartz impurities present in the sample; the presence of quartz was also evident in the x-ray powder patterns. The theoretical formula, $NaMgF_3$, requires F 54.64%, Na 22.05%, and Mg 23.31%.

The composition of this mineral was finally established by comparison with the artificial compound $NaMgF_3$ which can be easily synthesized in the laboratory by our method described below, or by a method described by Ludekens and Welch (1952) or by Blair Jones' method.

TABLE 1. SPECTROGRAPHIC ANALYSIS OF THE MINOR ELEMENTS OF NEIGHBORITE $NaMgF_3$, FROM SOUTH OURAY NO. 1 WELL, UINTAH COUNTY, UTAH†

Ca	0.5	La	0.02
Sr	0.3	Yb	0.01
Fe	0.2	Cr	0.01
Ti	0.06	Sc	0.01
V	0.05	B	0.005
Y	0.04	Cu	0.004
Zr	0.03	Be	0.0005

† Analyst: Nola B. Sheffey.

Our method of preparation consists of grinding stoichiometric proportions of NaF and MgF_2 in an agate mortar and then sintering the mixture in air at 750° C. for 5 hours. The fine-grained crystalline aggregate produced gives an x-ray powder diffraction pattern identical to that of the natural mineral neighborite (Table 2).

This compound has also been synthesized at much lower temperatures by Blair Jones at 300° C. and 30,000 bars water pressure and at 450° C. and 30,000 bars water pressure. Unfortunately, no single crystals suitable for x-ray investigation were produced.

The natural environment represented by the dolomitic oil shale in which neighborite occurs is that of a low temperature condition. Although the small amount of the mineral present seems geologically insignificant, the chemical environment was probably such that magnesium was abundant and aluminum deficient. The fluorine that was present therefore combined with sodium to form neighborite instead of cryolite.

CRYSTALLOGRAPHY

Buerger precession photographs of neighborite single crystals (using MoKα radiation) are consistent, to a first approximation, with a cubic unit cell having $a = 7.67$ Å. The optical properties, the lack of true symmetry planes shown by the intensity of the reflections, and poor quality of the single crystal patterns strongly suggested that the true symmetry of the crystal is lower than cubic, and that a pseudocubic aspect is produced by multiple twinning. After several crystals had been studied by the precession method, it seemed likely that the best chance of success in determining the cell constants and space group of neighborite lay in a study of the powder pattern.

The *x*-ray powder diffraction photograph of neighborite shows a remarkable resemblance to that of perovskite, $CaTiO_3$, both in *d*-spacing values and intensity of the reflections. As shown in Fig. 3 the correspondence is so good that there is no doubt that neighborite not only has the general perovskite type of structure, but also possesses the same type of distortions and superstructure of the simple cubic ABX_3 pseudo unit that are characteristic of perovskite itself. This hypothesis is amply confirmed by the detailed crystallographic and thermal measurements to be described in the following sections. Such a correspondence is not surprising in view of the close similarity of the radii of the ions involved:

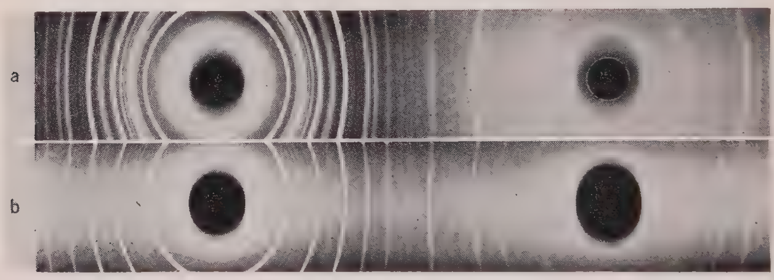

FIG. 3. *X*-ray powder diffraction patterns of (a) neighborite and (b) perovskite from Magnet Cove, Arkansas. (Patterns made with CuKα radiation, and a 57.3 mm. diameter camera.)

ABX_3	$CaTiO_3$	$NaMgF_3$
A	0.99 Å	0.95 Å
B	0.68	0.65
X	1.40	1.36

The powder diffraction data were measured from patterns made with film and the Philips diffractometer. Although the powder pattern of perovskite has never been correctly indexed, with the probable space group and the unit cell given for synthetic $CaTiO_3$ by Kay and Bailey (1957) the powder pattern of neighborite was successfully indexed. The cell dimensions of neighborite were determined from a careful measurement of the 200, 040 and 002 reflections on the diffractometer record. The measured and calculated data for neighborite are listed in Table 2. The dimensions of the unit cell and pseudocell are given in Table 3, in comparison with corresponding dimensions for $CaTiO_3$ as given by Kay and Bailey (1957). The statement by Ludekens and Welch (1952) that $NaMgF_3$ is tetragonal at room temperature (with $a=7.65$ and $c=7.30$ kX) is not supported by our work.

The specific gravity of neighborite calculated from the measured unit cell volume with 4 formula units per cell is 3.06, in good agreement with the value 3.03 ± 0.03 measured as described above.

Concerning the crystal structure of neighborite, no direct analysis of it is possible at this time, and we can only assume that it is closely similar to that of perovskite. We rely, therefore, on the penetrating study of this difficult problem made by Kay and Bailey (1957). They proved that the structure of $CaTiO_3$ has orthorhombic symmetry, and that the probable space groups are $Pcmn$ or $Pc2_1n$. By a detailed analysis of the structure, they concluded that $Pcmn$ is the correct one, and we may assume that neighborite, the stable low temperature phase, also has this space group. The crystal structure is described in a later section.

HIGH TEMPERATURE STUDIES OF NEIGHBORITE

Finely ground synthetic neighborite was mounted on the heating stage of a diffractometer. The heating stage was designed to provide a uniform temperature across the sample surface and temperatures were measured by means of a platinum-platinum-10 per cent rhodium thermocouple mounted at the center of the irradiated surface. The instrument was calibrated against the thermal expansion of silver and the melting point of silver. Temperature was controlled by means of an A.C. balancing bridge circuit in which the platinum heating element acted as one arm of the bridge. Temperature was controlled in this manner to ±2° C. for extended periods. Although neighborite is quite stable in air, the heating chamber was evacuated to reduce convection currents and allow a more satisfactory temperature control. In operation the heating stage allows the same resolution obtained with conventional diffractometer mounts at room temperature.

Preliminary heating runs established that neighborite became cubic at high temperatures, and that the high temperature cubic cell coincided with the pronounced cubic "pseudo cell" present at room temperatures. The melting point was not determined.

To investigate the transition from the orthorhombic cell at room temperature to cubic cell at high temperature, the lines 002, 200, 121, 022, 220 and 040 in the orthorhombic cell were accurately measured at a series of temperatures. It is most convenient to discuss the changes occurring in terms of the cubic "pseudo cell," rather than the true orthorhombic cell. Consequently, the parameters $a'=a/\sqrt{2}$, $b'=b/\sqrt{2}$ and

TABLE 2. *X*-RAY POWDER DATA FOR NEIGHBORITE, $NaMgF_3$
Orthorhombic, P*cmn* $a=5.36_3$, $b=7.67_6$, $c=5.50_3$ Å, (all ±.001 Å)
$a:b:c=0.698:1:0.717$

hkl	d_{hkl} (Å)calc.	Natural[1]		Synthetic[2]	
		d_{hkl} (Å)meas.	Intensity	d_{hkl} (Å)meas.	Intensity
110	4.396				
101	3.841				
020	3.838	3.83	35	3.85	44
111	3.435	3.44	4	3.44	7
002	2.751	2.75	4	2.75	17
121	2.715	2.71	50	2.71	54
200	2.682	2.68	4	2.68	11
012	2.590				
102	2.448	2.44	3	2.44	6
201	2.411	2.41	9	2.41	11
112	2.332	2.33	4	2.33	16
130	2.309	2.30	25	2.305	29
211	2.300			2.297	27
022	2.236	2.23	18	2.232	30
220	2.198	2.20	13	2.198	18
131	2.129	2.13	6	2.128	9
122	2.064	2.06	6	2.060	11
221	2.041	2.04	2	2.040	7
202	1.920				
040	1.919	1.918	100	1.918	100
032	1.874			1.872	3
212	1.863	1.862	4	1.862	4
132	1.769	1.765	2	1.765	3
231	1.755			1.755	4
310	1.741			1.743	3
103	1.736	1.732	3	1.733	7
222	1.717			1.716	10
141	1.717	1.713	9	1.713	6
301	1.700				
113	1.693	1.689	6	1.692	8
311	1.660	1.661	1	1.664	3
123	1.581			1.583	11
042	1.574	1.575	13	1.575	12
240	1.561			1.561	10
321	1.555	1.556	25	1.553	28
232	1.536	1.530	1		

[1] Natural neighborite, taken with film, camera diameter 114.59 mm. CuKα radiation ($\lambda=1.5418$ Å), Ni filter. Lower limit 2θ measurable: approximately 6.3° or 14.04 Å.

[2] Synthetic neighborite, using diffractometer, CuKα radiation ($\lambda=1.5418$ Å), Ni filter. Sample contains a trace of NaF, not reported.

TABLE 2 (*continued*)

hkl	d_{hkl} (Å)calc.	Natural[1]		Synthetic[2]	
		d_{hkl} (Å)meas.	Intensity	d_{hkl} (Å)meas.	Intensity
142	1.510				
241	1.501				
302	1.499	1.499	2	1.497	2
213	1.485				
150	1.476	1.473	2	1.475	2
312	1.471				
330	1.465				
133	1.436	1.434	2	1.435	2
151	1.426				
331	1.416	1.415	1	1.415	1
223	1.408	1.404	1	1.406	1
322	1.396				
004	1.376	1.371	3	1.373	4
242	1.357	1.356	13	1.355	15
		1.340	2	1.340	3
		1.327	2	1.329	2
		1.300	4b	1.298	4
		1.282	3b	1.284	3
		1.268	1b		
		1.256	1b		
		1.234	2	1.233	1
		1.220	2	1.222	1
		1.213	4	1.212	5

TABLE 3. UNIT CELL DIMENSIONS OF SYNTHETIC NEIGHBORITE AND PEROVSKITE
Data for CaTiO$_3$ from Kay and Bailey (1957)

	NaMgF$_3$ (18° C.)	CaTiO$_3$ (Temp. not stated)
a	5.363 ± 0.001 Å	5.3670 ± 0.0001 Å
b	7.676 ± 0.001	7.6438 ± 0.0001
c	5.503 ± 0.001	5.4439 ± 0.0001
$a:b:c$	0.6987:1:0.7169	0.70213:1:0.71219
$a' = a/\sqrt{2}$	3.792 Å	3.7951 Å
$b' = b/2$	3.838	3.8219
$c' = c/\sqrt{2}$	3.891	3.8494
$a':b':c'$	0.9880:1:1.0138	0.99298:1:1.00719
V′	56.63 Å^3	55.834 Å^3

$c' = c/\sqrt{2}$ (where a, b, and c are the unit cell edges of the orthorhombic cell) were calculated from the measurements and these are presented in Table 4, and illustrated in Fig. 4.

With rising temperature neighborite remains clearly orthorhombic, although the a' and c' lengths become progressively closer together. At 760° C., and a' and c' lengths become identical, an effect which can best be observed by the coalescence of the 220 and 022 lines. Above 760° C., a' and c' remain identical but b' is still measurably less than a'. The cell is now tetragonal or pseudo-tetragonal. At 760° C., all reflections with orthorhombic indices k odd, and those with k even and $h+l$ odd disappear, indicating that the tetragonal cell is congruent with the former "pseudo cell." The unit cell edges of the new tetragonal cell at this temperature are $a=b=3.942$ Å and $c(=b')=3.933$ Å. The transformation matrix from the orthorhombic cell to the tetragonal cell is

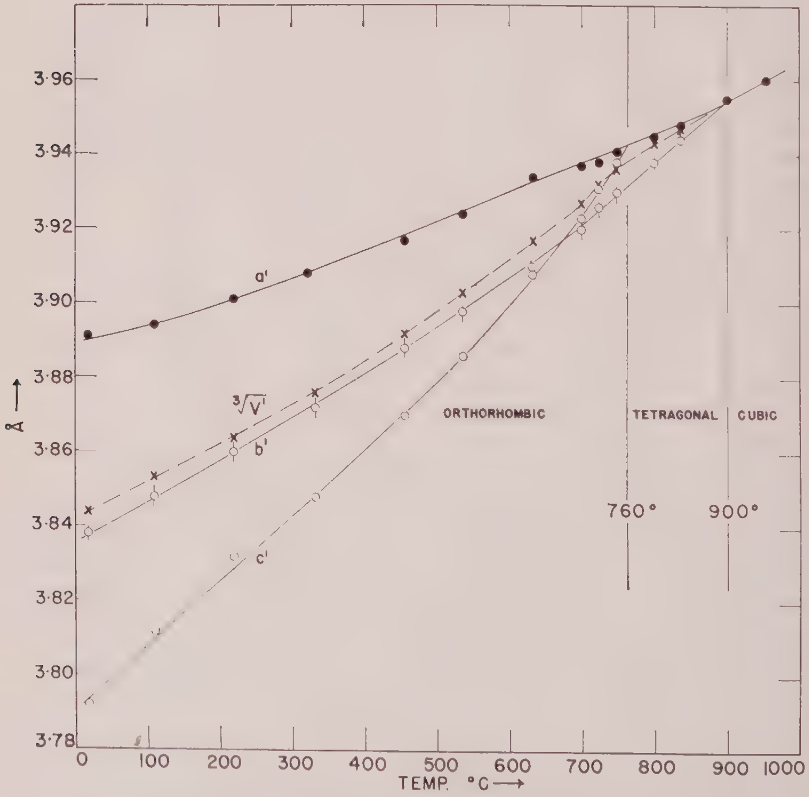

FIG. 4. Variation in cell constants of neighborite with temperature, showing transition points at 760° C. and 900° C.

TABLE 4. DIMENSIONS OF THE CUBIC PSEUDOCELL IN NEIGHBORITE AT DIFFERENT TEMPERATURES

Temp. ° C.	a' Å	b' Å	c' Å	$\sqrt[3]{V'}$ Å
Orthorhombic				
18	3.792	3.838	3.891	3.842
110	3.812	3.848	3.894	3.853
220	3.832	3.860	3.901	3.864
333	3.848	3.872	3.908	3.876
457	3.870	3.888	3.917	3.892
537	3.886	3.898	3.924	3.903
633	3.908	3.910	3.934	3.917
700	3.923	3.920	3.937	3.927
724	3.931	3.926	3.938	3.932
749	3.938	3.930	3.941	3.936
Tetragonal				
800	3.945	3.938	3.945	3.943
837	3.948	3.944	3.948	3.947
Cubic				
900	3.955	3.955	3.955	3.955
954	3.960	3.960	3.960	3.960

In the orthorhombic phase, $a=\sqrt{2}\cdot a'$, $b=2b'$, $c=\sqrt{2}\cdot c'$; in the tetragonal phase, $a=a'$ $=c'$; $c=b'$; in the cubic phase, $a=a\ =b'=c'$. $V'=a'b'c'$, the volume of the pseudocell.

$\frac{1}{2}\frac{1}{2}0\frac{1}{2}/\frac{1}{2}$, 0, $-\frac{1}{2}/0\frac{1}{2}0$. Figure 5 shows the diffractometer records of the cubic phase at 900° C. and the orthorhombic phase at 18° C. From 760° to 900° C. neighborite remains tetragonal, but the axes gradually become closer in length. Above 900° C. the three axes become identical and the cell is cubic. Designation of the transition temperature as 900° C. is largely based on the projection of the a' and b' axial lengths versus temperature plots. Since the curves converge at a small angle the intersection point necessarily has a large uncertainty and the tetragonal→cubic transition temperature should be considered as 900°±25° C.

The progressive transitions from orthorhombic to tetragonal to cubic can best be demonstrated by observing the 200, 002 and 121 reflections. At 760° C. the 200 and 002 lines become coincident but are still clearly resolvable from the 121. At 900° C. all three lines become coincident reflecting the cubic cell. The transitions are rapidly reversible and to our knowledge the tetragonal and cubic forms cannot be quenched to room temperature.

A plot of the cube root of the volume of the "pseudo cell" against temperature (Fig. 4) has a small inflexion at 760° C. and another at approximately 900° C. Since no abrupt break in the curve is observed both

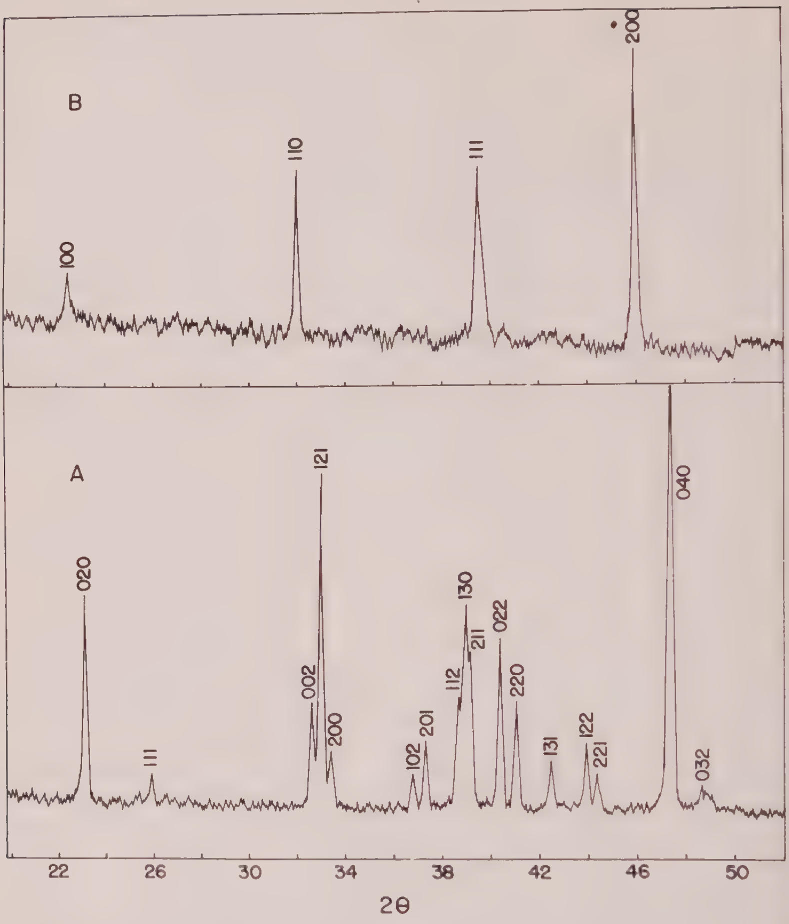

FIG. 5. *X*-ray diffractometer traces of neighborite at (A) 18° C. and (B) 900° C., CuKα radiation, demonstrating disappearance of superlattice lines in the higher temperature form.

the orthorhombic→tetragonal and tetragonal→cubic transitions are at least second order and possibly higher order, transitions.

CRYSTAL CHEMISTRY

Neighborite belongs to the simple class of crystal structures with general formula ABX_3, commonly known as the "perovskite family" (Wells, 1950, Megaw, 1957). The ideal structure is cubic with a unit cell about 3.8 to 4.0 Å on edge, containing one formula unit. The structure consists of A and X atoms in cubic closest packing with B atoms inserted in octa-

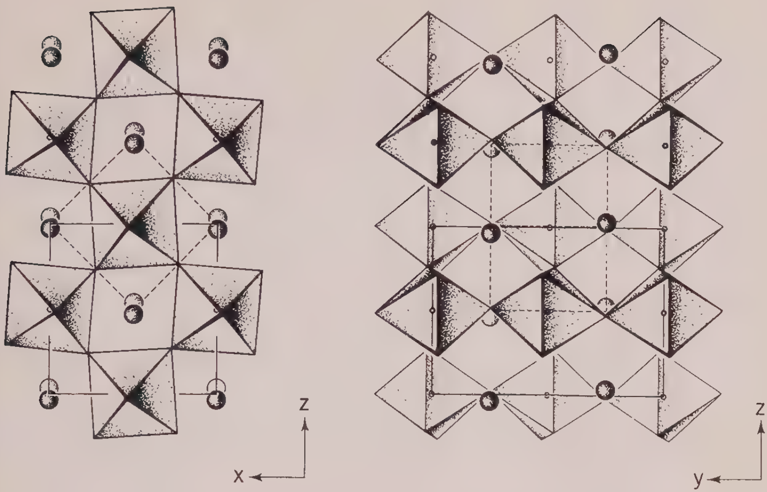

FIG. 6. Schematic views of the probable crystal structure of neighborite, after the structure described for perovskite by Kay and Bailey (1957). Na atoms are represented by large shaded spheres, Mg atoms by small circles and MgF_6 groups by shaded octahedra. Full lines outline the orthorhombic unit cell and dashed lines show the cubic pseudocell. The Na atoms lie on mirror planes normal to the *y* axis, seen on edge in the view at right.

hedral cavities. If the A atom is significantly smaller or larger than X, the simple structure is generally distorted to a lower symmetry. Thus, in perovskite itself, for which calcium is a little more than half the size of oxygen, the symmetry becomes orthorhombic and a superstructure is formed with a unit cell four times the size of the ideal cell. Such distorted structures often transform to the ideal structure type at some higher temperature, and for perovskite, there is evidence that such a transition does occur at about 1260° C. (Megaw, 1957, p. 91). In the heating experiments on synthetic neighborite, this transition was positively identified at 760° C.

On the basis of their single crystal intensity data alone, Kay and Bailey (1957) could not distinguish between two possible structures for $CaTiO_3$. One of these two resulted in highly distorted octahedra with Ti-O distances ranging between 1.78 and 2.08 Å. The other (shown in Fig. 6) has fairly regular octahedra (Ti-O distances all 1.93 Å), the distortion of the high temperature cubic structure being manifested only in the tilting of the polyhedra. Kay and Bailey accepted the latter mainly on grounds of parsimony, even though other structures such as $BaTiO_3$ and $PbTiO_3$ (Megaw, 1947, p. 108) show large distortions in the TiO_6 octahedra. The cause of the distortion in the perovskite structure has been commonly attributed to the relatively small size of the calcium atom. Kay and Bailey's proposed structure effectively reduces the coordination for calcium from 12 (for the undistorted high temperature form) to 8 (8 Ca-O distances of 2.4–2.5 Å; the other 4 become 3.0–3.1 Å).

Since it is well known that titanium can suffer considerable distortion of its bonding with oxygen, presumably because of the largely covalent character of the bonds and the influence of the available 3*d* orbitals in forming hybrids in the formation of these bonds, the crystal chemical arguments for the $CaTiO_3$ structure presented above do not rest on a firm theoretical basis. The situation is different for neighborite, however. Here the bonding is largely ionic, and no *d*-hybridization is possible. Therefore, there is no reason to expect the MgF_6 octahedra to depart from regularity any more than is necessary, and the tilted regular octahedron structure can be accepted with much more assurance. Fortunately, the close analogy between the structures of $NaMgF_3$ and $CaTiO_3$ strengthens the arguments set forth by Kay and Bailey for this structure for the latter.

The appearance of the tetragonal phase between the low temperature orthorhombic and high temperature cubic forms does not have any obvious explanation. The tetragonal cell consists of a slight distortion of the cubic cell ($c/a=0.9977$ at 760° C.), similar to that of $BaTiO_3$, which is cubic above and tetragonal below 120° C., the latter phase having $c/a=1.009$ (Megaw, 1957). The tetragonal distortion in $BaTiO_3$ is certainly due to a pronounced polarization of one of the Ti-O bonds (Evans, 1953) of a kind which has frequently been found in transition metal oxide and fluoride structures. Such a polarization seems implausible in an ionic magnesium fluoride structure, and we believe that the explanation more probably lies in some special type of thermal vibration. As the temperature of the orthorhombic form is increased, the degree of tilting of the octahedra in the *a-c* plane (Fig. 6, top view) must become less and less until at the transition temperature 760°, the pattern becomes quite square. If the Mg-F-Mg links which tie one layer normal to the new tetragonal axis to the one above or below is still bent as it was in the orthorhombic phase, the tetragonal *c* axis ($\frac{1}{2}$ the orthorhombic *b* axis) would be slightly shortened with respect to the *a* axis, as is observed. This shortening may be contrasted with the slight lengthening which results from bond polarization as in $BaTiO_3$ and $PbTiO_3$. The bending of the bond would be randomly oriented with respect to the tetragonal *c* axis, corresponding to a libration of the fluorine atom about the Mg-Mg axis. The reason why such libration might be emphasized only on alternate fluorine layers in the structure is not revealed by our speculation.

References

Evans, H. T., Jr. (1953) An *X*-ray diffraction study of barium titanate: *Technical Report No.* **58**, *Laboratory for Insulation Research, M.I.T.*, Cambridge, Mass.

Kay, H. F., and Bailey, P. C. (1957) Structure and properties of $CaTiO_3$: *Acta Cryst.* **10**, 219–226.

Ludekens, W. L. W., and Welch, A. J. E. (1952) Reactions between metal oxides and fluorides: some new double-fluoride structures of type ABF_3: *Acta Cryst.* **5**, 841.

Megaw, H. D. (1957) Ferroelectricity in Crystals: Methuen and Co. Ltd., London, 236 p.

Wells, A. F. (1950) Structural inorganic chemistry, 2nd ed: The Clarendon Press, Oxford.

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GIBBSITE VERMIFORMS IN THE PENSAUKEN FORMATION OF NEW JERSEY

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Abstract

Vermiform aggregates found in seven localities in the coarse sands of the Pensauken formation were identified as composed mostly of gibbsite. Although their appearance is very similar to kaolinite vermiforms and knaeuel described in the literature, all indications are that they are authigenic and formed by direct weathering of feldspar and other silicates to gibbsite, suggesting a near-laterite type of weathering during an interglacial period of the Pleistocene in this area.

Introduction

Vermiform crystal aggregates of kaolinite, dickite, and anauxite have been reported by Ross and Kerr (1930) and others (Carozzi 1960), usually associated with kaolin deposits. Kulbicki (1954) describes vermicular dickite in a gibbsite matrix. Gordon and Tracey (1952) found accordionlike kaolinite crystals partly replaced by gibbsite in the bauxites of Arkansas.

Vermicular aggregates of appearance strikingly similar to some of these were found by J. H. C. Martens (personal communication) in the Pensauken formation near South Amboy, New Jersey. These vermiforms are much larger in size, however, than those reported elsewhere, and their principal constituent was identified as gibbsite (Lodding 1960).

Occurrence

Vermicular gibbsite aggregates were found since then in six additional localities of the Pensauken formation, as indicated in Table I. They occur in coarse and medium size arkosic sand and gravel. Considering the delicate shapes and little strength of some of these aggregates it is difficult to imagine that they underwent any amount of transportation. It must be assumed that they are authigenic. Gibbsite was also found in the same localities as a whitish cement, filling interstices between the sand grains. Although gibbsite cement is present in some glauconitic sands, no vermiforms were found to date in sands containing glauconite.

Five of the seven localities described lie within a circle of six miles south of the Raritan River estuary. Samples No. 960 and 1081 were found 20 and 30 miles to the south-east of this area. No preferential vertical distribution has been observed.

The thickness of the gibbsite-bearing beds is rather irregular mainly due to cross-bedding. Although it is sometimes possible to follow a horion for several hundred feet, its thickness may vary from a few inches o several feet. The spans indicated in Table 1 are those encountered at particular bore hole or channelled exposure.

Description of Specimens

Vermicular gibbsite aggregates range in size from 1 to 6 mm. in their ongest dimension, with length-to-width ratios varying between 1 and 0. (Fig. 1)

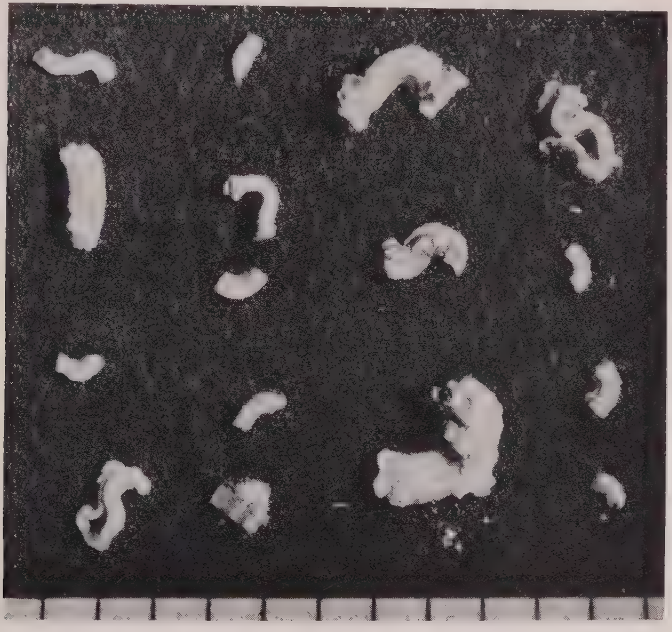

FIG. 1. Vermicular gibbsite. Each scale division = 1 mm.

The color of the aggregates ranges from off-white to light brown. A ew specimens show a heavy surface coating and are almost black. Branching along longitudinal cracks is frequent. Some twisted vermicular ggregates very similar to the Kaolinitknaeuel described by Guthörl 1956) are also found. Many vermiforms show brown banding perpenicular to their long axis. Unlike that in the kaolinite vermiforms decribed by Schüller, the brown banding is not due to organic matter, but o iron oxides.

Vermiform gibbsite shows some cleavage perpendicular to the long xis. Thus mica-like platelets are sometimes obtained by prodding a ermiform with a needle. These platelets have the shape of irregular hexagons, parallelograms, or a composite of these figures, often with reentrant angles.

Delicate water-clear skeletal particles of plagioclase (as identified by J. H. C. Martens) are often found in the coarse sands.

COMPOSITION

Chemical and spectrographic analyses were made on hand picked vermiforms of sample 1013. The chemical analysis showed the following:

Al_2O_3	57.0 %	MnO	0.05
SiO_2	7.41	CuO	0.02
Fe_2O_3 (total)	4.32	Na_2O	0.12
TiO_2	1.80	K_2O	traces
MgO	0.14	Loss on ign.	28.7
CaO	0.04		
SrO	0.01	Total	99.61%

X-ray powder photographs show strong reflections for gibbsite and weak lines for kaolinite and quartz. No reflections were found for iron oxides, suggesting poorly crystalline or amorphous compounds. A Laue photograph taken on a single vermiform platelet with the beam perpendicular to the presumed *a–b* plane showed that the platelet is clearly not a single crystal, although a certain degree of preferred orientation can be observed.

Differential thermal analysis showed the endothermic reaction for the dehydration of gibbsite starting at 250° and the peak at 335° C. A small kaolinite peak is at 550°, and a small amount of quartz is indicated by the α-β inversion at 573°. No evidence of dickite was found in 38 thermograms.

DTA was performed both in dynamic air, or in hydrogen atmosphere followed by oxidation in air. The latter method was used to distinguish between hydrated iron oxides and gibbsite, which both dehydrate in the same temperature range, when heated in air. (Lodding and Hammell 1960.) The approximate amount of gibbsite present was determined by these methods in all vermiform-bearing sands shown in Table I.

From the chemical analyses and DTA the mineral composition of sample 1013 was calculated:

gibbsite	87%
kaolinite	6%
iron and titanium oxides	6%
quartz	1%

Vermiforms from other localities have a similar mineral composition except for the gibbsite-kaolinite ratio, which may vary from 15 to 3. Op-

TABLE 1. OCCURRENCE AND DESCRIPTION OF VERMICULAR GIBBSITE

Sample No.	Thickness Inches	Location	Gibbsite	Vermiforms		Total* Gibbsite	Matrix
			Max. length	Color	Abundance		
951	18	Wright Tract South River	—	—	—	10%	very coarse glauconitic sand, slightly cemented, off-white
1007	18	Wright Tract South River	2 mm.	buff to brown	1%	10%	fine white sand, crumbly buff cement
1013	12	Wright Tract South River	6 mm.	buff to brown	5-10%	20%	medium yellow to brown sand
1019†	12	Wright Tract South Tract	3 mm.	buff to black	1-10%	10%	medium red and yellow sand black and brown crumbly aggregates
961	6–24	Whitehead Ave. East Brunswick	2 mm.	buff	1%	20%	coarse light brown to gray sand, abundant white crumbly cement
982 and 924	10–24	Sayre & Fisher Sand Co. Sayreville	2 mm.	buff	1%	15–20% 3%	white to yellow feldspathic sand, brown yellow or white crumbly cement
992	20	Crossman Co. South Amboy	1.5 mm.	buff	1%	2%	feldspathic coarse sand, colorless to heavily coated by brown and black oxides, white cement
996	10–20	Whitehead Ave. Oldbridge	2 mm.	light buff	1%	3%	medium light sand, much white crumbly cement, black and brown aggregates
1084	6–12	Windsor, N. J.	2 mm.	white to buff	1%	6%	white gravel, feldspathic sand, light brown clay
960†	2×4	Columbus, N. J.	3.5 mm.	white to buff	1-5%	15–20%	medium red brown sand, heavily coated, white crumbly cement

* As determined by DTA
† Collected by James Bowman II.

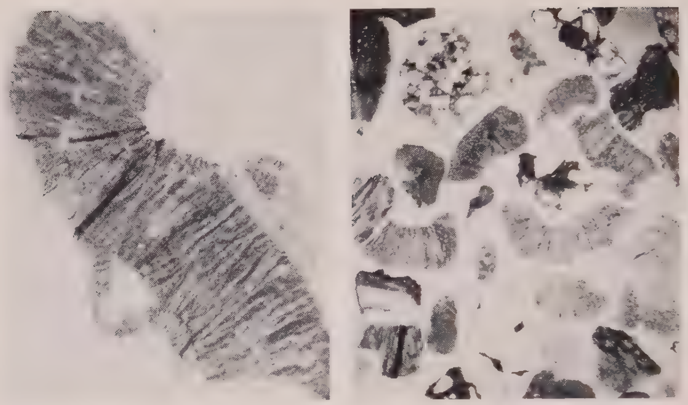

Fig. 2. Vermicular gibbsite; undisturbed thin sections. Left: ×40; right: ×14.

tical Properties: Indices α,β 1.566±0.002; α appr. 1.585 (all except fragments very high in limonite 1.584), 2V estimated 10°, sign positive.

Thin Sections

Undisturbed sections were prepared from slightly consolidated vermiform-bearing sands. See Figs. 2 and 3. Orientation of the gibbsite seems to be random and little relation is apparent between quartz aggregates and vermiforms. Gibbsite vermiforms often split parallel to their long axis, and sometimes these branches double back to the main body (Fig. 2). These branches look like the result of longitudinal cracks, causing a peculiar angular cross section of the vermiform gibbsite platelets described. In Fig. 3 a gibbsite vermiform is seen in polarized light with the extinction boundaries following the rotation of the moving stage. No

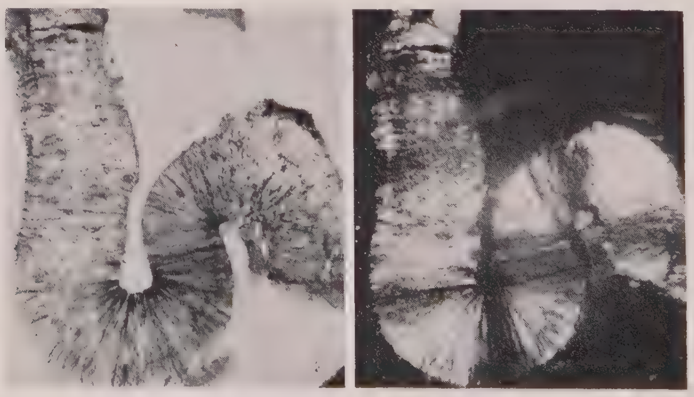

Fig. 3. Vermicular gibbsite. Left: plane polarized light; right: crossed nicols. Both ×40.

evidence of vermiforms growing on muscovite platelets as described by Schüller (1951) was seen. The gibbsite vermiforms seem to be detached from the other mineral grains and aggregates with only point contacts between them.

GENESIS OF VERMIFORM GIBBSITE

The Pensauken formation is composed of sand, gravel, silt and clay, often deeply eroded and weathered. According to Salisbury and Knapp (1918) and MacClintock (1940) it is interglacial, younger than the Bridgeton and older than the Cape May (Sangamon) formations. It is thought to be a stream deposit laid down by rivers with shifting channels as evidenced by frequent cross bedding. The permeable Pensauken sands are not covered by any other formation and apparently have not had much of any cover in their past history.

Vermiforms are found at depths of three to twenty feet below the present surface. The presence of abundant feldspar in various stages of weathering in the Pensauken points to the source of alumina needed to form gibbsite. Keller (1958) proposes a mechanism of direct weathering of nepheline, amphiboles and feldspars to kaolinite, gibbsite, and iron oxides. Weathering in a pH range of 7 to 9.5 may lead to removal of silica and iron, leaving aluminum hydroxides behind. At higher pH, both alumina and silica are mobile, and at a pH below 7 alumina is immobile and silica has low mobility. Abrasion pH values of 9 to 11 are obtained when nepheline, diopside, or feldspars are ground. In the presence of these minerals, rain and ground water may acquire a pH between 7 and 9.5. Such a condition may produce preferential leaching of silica in the weathering of aluminous silicates. Aluminum hydroxide left behind may partly dehydrate and crystallize to gibbsite on suitable seed crystals.

An alternative possibility would be the formation of kaolinite vermiforms as the result of feldspar weathering, and subsequent transformation of the kaolinite into gibbsite by the removal of silica. This process appears less likely in the present case, because of the absence of kaolinite vermiforms in the Pensauken. It is likely that some of the verniforms ound in seven different localities of the Pensauken would have remained kaolinite, if this had been the starting material. The fact that kaolinite constitutes at most one-fourth of the vermiforms, and usually much less, would indicate the likelihood of direct weathering of pyroxenes and feldpars to gibbsite. Incomplete removal of the silica can then account for the kaolinite present.

Keller (1958) lists the following conditions leading to the formation of gibbsite:

1) parent materials with an abrasion pH of 9 or higher.
2) profuse rainfall throughout the year.
3) high temperature (accelerating rate of hydrolysis).
4) abundant and continuously active microflora of very warm humid climate.
5) high permeability of regolith which allows the removal of dissolved silica.

Conditions corresponding to points one and five are evident in the Pensauken formation. Some evidence is also present for the existence of conditions two, three, and four, which assume a hot and humid climate and rapid weathering and oxidation representing a near-laterite type of weathering. The scarcity of organic matter and the state of oxidation of iron as heavy coatings on sand grains and in the clays point in this direction.

In this connection it should be noted that Krebs and Tedrow (1958) recently identified gibbsite as a major constituent of the clay fractions in certain soil horizons in two widely separated areas of New Jersey. The Annandale loam and silt loam derived from the pre-Wisconsin glacial drift on Schooleys Mountain and the Aura and related sandy loams derived from the Bridgeton formation all contain considerable gibbsite and kaolinite.

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REFERENCES

CAROZZI, A. V. (1960); Microscopic Sedimentary Petrography, John Wiley, N. Y.

GORDON, M., JR., TRACEY, J. I., JR. (1952); Origin of the Arkansas Bauxite Deposits, *Clay and Laterite Genesis*, **AIME** pp. 12–34.

GUTHÖRL, P., HOEHNE, K., SCHÜLLER, A. (1956); *Monographie der Saartonsteine, Teil I, Geologie*, **5**, 695–755.

KELLER, W. D. (1958); Argillation and Direct Bauxitization in Terms of Concentration of Hydrogen and Metal Cations at Surface of Hydrolizing Silicates, *Bull. AAPG* **42**, 2, 233–245.

KREBS, R. D., TEDROW, J. C. F. (1958); Genesis of Red-Yellow Podsolic and Related Soils in New Jersey, *Soils Sci.* **851**, 28–37.

KULBICKI, G. (1954); Phenomènes de diagenèse dans les sediments argileux; *Clay Min. Bull.* **2**, 12, 183–187.

LODDING, W. AND HAMMELL, L. (1960); DTA of Hydroxides in Reducing Atmosphere, *Anal. Chem.* **32**, 6, 657–662.

odding, W. (1960); Vermicular Gibbsite in the Pensauken of New Jersey, *Am. Mineral.* **45,** 228–229.

MacClintock, P. (1940); Weathering of the Jersyean Till, *Geol. Soc. Am. Bull.* **51,** 103–116.

Ross, C. S. and Kerr, P. F. (1930); The Kaolin Minerals, *U.S.G.S. Prof. Paper* **165-E,** 151–176.

alisbury, R. D., Knapp, G. N. (1917); The Quaternary Formations of Southern New Jersey, *N. J. Dept. of Conserv. & Dev. Final Report* **8,** 218 pp.

chüller, A. (1951); Zur Nomenklatur und Diagenese der Tonsteine, *N. Jahrb. Min Monatsheft* **5,** 92–109.

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URANO-ORGANIC MINERAL ASSOCIATION

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ABSTRACT

Semi-fluid asphalt which percolates through uranium ore bodies on the San Rafael Swell is indurated by heat at temperatures from 250° C.–300° C. The indurated material becomes brittle and generally similar in physical properties to naturally indurated "asphaltite." Infrared curves of artificially indurated material also compare favorably with curves for natural "asphaltite." Infrared curves for both indurated artificial and natural "asphaltite" show weak and indistinct absorption bands in contrast to the stronger absorption of semi-fluid asphalt.

Mineralogical investigation of the uranium silicate coffinite indicates that the mineral is similar to the synthetic coffinite, prepared by Fuchs and Hoekstra (1959), through the absence of an essential hydroxyl component.

The intimate and widespread association of indurated uranium-bearing "asphaltite" and the uranium silicate coffinite suggests that the two were formed contemporaneously. The urano-organic constituent could presumably have been hardened by irradiation, although this seems unlikely. However, such an origin is hardly even conceivable for the uranium silicate coffinite. Hydrothermal origin is believed to prevail both for the coffinite and the associated uranium "asphaltite."

INTRODUCTION

The widespread asphaltic association of uranium has long been recognized, and most workers attribute a petroliferous origin to this material. On the other hand, there appears to be a lack of agreement on the original source of the uranium and the temperature of formation. Gott and Erickson (1952) have suggested that uranium might have concentrated in the asphaltites directly from petroleum. Erickson *et al.* (1954) have also indicated that the similarity between the metal suite in crude oils and in uraniferous asphaltic deposits, and the uranium concentration in the latter, suggest that uranium and the other metals have accumulated in the heavier, more asphaltic portions of petroleum Several believe that uraniferous asphaltites may have been formed through volatilization, oxidation, and polymerization of a petroleum enriched in these metals. Hail *et al.* (1956), however, concluded that most of the uranium present in the oil has been introduced during migration. At the same time, Breger and Deul (1956) have indicated that petroleum can be both a carrier and a collector of uranium.

Polymerization or condensation of hydrocarbons around an older radioactive source as a result of irradiation has been suggested by Elsworth (1928), Spence (1930), Davidson and Bowie (1951), Davidson (1955), Isachsen and Evensen (1956), and Pierce *et al.* (1958).

The exceedingly low uranium content of crude oils and asphalts compared to the high content in uraniferous asphaltites indicates that petroleum is more likely to be a collector than a distributer of uranium. Keiley and Kerr (1958) have suggested that uranium-bearing hydrothermal solutions have introduced that metal into pre-existing liquid hydrocarbons which were indurated by the accompanying heat.

In this asphaltic association, uranium may be found in discrete minerals such as uraninite or coffinite, and it may occur as a urano-organic complex. The temperature range under which coffinite forms (Fuchs and Hoekstra, 1959) and the temperature of induration of "asphaltite" are believed to be significant in the interpretation of the temperatures which prevailed during uranium mineralization on the Colorado Plateau.

The objective of the current study has been essentially twofold: (1) to study the effect of heat on semi-fluid asphalt collected from fissure seepages in certain uranium deposits in order to compare the heat-treated material with naturally occurring uranium-bearing "asphaltite" from the same area, and (2) to study the association of coffinite, a frequent accompaniment of "asphaltite," in order to obtain more information on the nature of this unusual mineral and the significant association involved.

Indurated Uranium-Bearing Asphaltite

Numerous uranium deposits contain impregnations of asphaltic materials in which the impregnated rock types (Pierce *et al.*, 1958) range from igneous and metamorphic to terrestrial and marine sedimentary.

Elsworth (1928) applied the name thucholite to a thorium-uranium-rare earth hydrocarbon found in pegmatites at Parry Sound, Ontario. Thucholite was believed by Elsworth to have been formed by hydrothermal replacement of uraninite by hydrocarbons polymerized by α-particle irradiation. Spence (1930) believed that migrating mineral oil was polymerized by radiation to form thucholite which in turn replaced uraninite.

Christie and Keston (1949) have described thucholite associated with gold in pitchblende veins in the Goldfields district of Saskatchewan, Canada. Bowie (1955) concluded that thucholite from the Nicholson mine, Saskatchewan had resulted from the polymerization of mobile, mostly gaseous hydrocarbons by radiation emitted by pre-existing pitchblende, a process similar to that postulated by Davidson and Bowie (1951) for the hydrocarbon-uraninite complex of the Isle of Man and the Witwatersrand.

Uraniferous hydrocarbons from Moonta, South Australia have been reported by Mawson (1944) in lodes cross-cutting bornite and quartz.

Davidson and Bowie (1951) studied a sample from this occurrence and found fine pitchblende associated with chalcopyrite, bornite, covellite, arsenopyrite, and quartz.

Linares (1956) has reported a uranium-bearing asphaltic material (thucholite) associated with uraninite, copper sulphides, galena, and sphalerite from the Eva Peron deposit of the Argentine Republic. The asphaltic material is thought to have originated through distillation of bituminous mud by thermal action related to magmatic activity. Uraniferous asphaltites have also been reported in the Soviet Union, Japan, Sweden, and Mexico.

In the United States occurrences of uranium-bearing "asphaltite" are widespread on the Colorado Plateau and in adjacent areas, but the nature and origin of such occurrences has been the subject of considerable discussion.

Breger and Deul (1955) have suggested that organic pellets in the Moss Back formation of the San Rafael Swell represent an organic extract from low-rank coals. Kelley and Kerr (1958) pointed out, however, that important factors of field occurrences support a petroliferous origin. Drill holes on the east side of the Temple Mountain show the transition from indurated uranium "asphaltite" to viscous non-uranium asphalt. There is also a widespread distribution of oil sand in the permeable strata of the area. At the same time coal is absent and the distribution of lignitic material is sparse.

Hydrocarbon occurrences of the Unita basin (Hunt *et al.* 1954) show four chemically different types (ozocerite, albertite, gilsonite and wurtzilite) which are believed to represent variations in the depositional environment of the source rock. Davidson (1955) has stated that many specimens of uraniferous "asphaltite" from the Plateau are indistinguishable under the microscope from thucholite derived from hydrothermal lodes or pegmatites and has expressed the opinion that both occurrences have a common origin.

Pierce *et al.* (1958) report that study by x-ray diffraction and infrared absorption with chemical organic analyses of various mineral oils and uraniferous "asphaltite" suggest a petroliferous origin for much of the "aslphaltite" in the western United States.

Erickson *et al.* (1954) and Hail *et al.* (1956) have suggested that uranium which is present in small amounts in crude oil tends to be concentrated in the heavier, more asphaltic portion of the oil as an urano-organic complex and suggest crude oil as a transporting medium for uranium. However, analyses of many crude oil samples show only a few parts per billion of uranium, while in refinery residues the uranium content has been found by Hyden (1956) to lie within the comparatively low range of 0.33 to 1070 parts per billion. McKelvey *et al.* (1956) concluded that it is unlikely that migrating petroleum is the source of uranium in the Colorado Plateau. Kelley and Kerr (1958) have shown that an average urano-organic ore sample from Temple Mountain represents a uranium concentration two million times greater than the associated crude oil. They have concluded that the bulk of the uranium must have been provided by hydrothermal solutions. Breger and Deul (1956) also believe that water, because of its powerful solvent action, is probably the most effective medium for transporting uranium from its source to its eventual site of concentration in carbonaceous substances.

The highly irregular distribution of uranium in asphaltic ore and the wide occurrence of essentially non-radioactive, indurated material in the same localities support the conclusion that the asphaltic material is essentially a collector of uranium rather than a major transporting medium.

Infrared Absorption of Uranium-Bearing Asphaltite

Infrared absorption curves have been obtained from viscous asphalt and from three samples of the same material heated in an electric oven at temperatures of 100°, 200°, and 300° C. each for 72 hours. The asphalt was collected from fissure seepages which cut the uranium ore body in the Magor mine, San Rafael Swell, Utah.

The infrared curve of the unheated material (Fig. 1, curve No. 1) shows strong absorption at 3.4 μ, 6.8 μ, and 7.2 μ indicating aliphatic structures. It is identical in its principal absorption bands to a carbonaceous nodule from the Seven Rivers formation, Eddy County, New Mexico (Pierce *et al.* 1958, p. 193). According to Pierce et al. (1958) the 3.4 μ band is caused by stretching by aliphatic C-H groups, while 6.8 μ and 7.2 μ indicate bending by methylene CH_2 groups and terminal CH_3 groups respectively. A weak absorption band at 5.8-5.9 μ indicates acid carbonyl $(C=O)$ groups. Although the absorption band near 6.3 μ falls in the region of aromatic absorption, the absence of aromatic absorption at 3.2–3.3 μ suggests that the 6.3 μ band is largely caused by water. The intensity of the 2.95 μ band tends to decrease greatly by prolonged evacuation, indicating water.

At 100° C. the asphaltic material shows increased fluidity compared to the highly viscous unheated material. At 200° C. (Fig. 1, curve No. 2) the major absorption peaks are essentially identical with those of the unheated material and the 100° C. product. Partial induration occurs at 200° C. as indicated by an increase in viscosity and the tendency of the material cooled to room temperature to fracture conchoidally. The average hardness of a semi-fluid tar from Temple Mountain was found (Kelley and Kerr, 1958) to be 3.4 Knoop after being heated at 200° C. for 96 hours, and 10.7 Knoop after being heated at the same temperature for 142 hours.

At 300° C. a sharp decrease in the intensities of the aliphatic absorption bands at 3.4 μ, 6.8 μ, and 7.2 μ takes place (Fig. 1, curve No. 3) and is accompanied with increased induration. The product becomes brittle, with a conchoidal fracture, and the infrared absorption curve becomes similar to the infrared absorption of the uraninite-bearing "asphaltite" from Flat Top Mountain and the Tomsich Mountain localities of the San Rafael Swell, Utah (Fig. 1, curves No. 4 and 5). The major difference between "artificial" and natural "asphaltites" lies in the presence of silica absorption in the 9–10 μ region caused by the presence of quartz in the Flat Top material and sulphur absorption near 8.9 μ caused by pyrite in the Tomsich Mountain material.

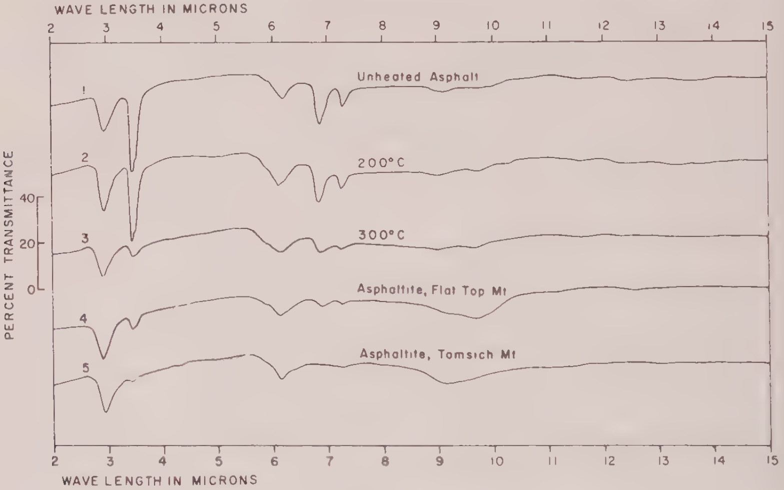

FIG. 1. The effect of heat on the infrared absorption of asphalt.

X-ray diffraction of semi-fluid asphalt, the heat-indurated (300° C.) product cooled to room temperature, and natural "asphaltite" from Flat Top Mountain show a single diffuse halo centered around the "*d*" spacing of 4.9 Å.

The experiment does not reveal the nature of changes during the heating process which resulted in the virtual disappearance of the absorption bands of the semi-fluid asphalt. It is conceivable that a combination of devolitilization, oxidation, and polymerization takes place.

However, the similarity between the heat-treated product of the semi-fluid asphalt and the natural "asphaltite" in physical appearance and infrared absorption suggests the induration of natural "asphaltites" by high temperatures in the range 250°–300° C. as would be expected under hydrothermal conditions.

The effect of irradiation on hydrocarbons which causes polymerization and other radiation damage effects is widely recognized and may be an important factor in the induration of uranium-bearing asphaltic materials. Pierce *et al.* (1958) have shown that the total internal radiation dosage received by a number of "asphaltites" ranges from 10^{24} to 10^{27} electron volts per gram which corresponds to levels at which organic compounds are converted to coke in nuclear reactors. The indurated materials reported carry uranium or thorium in ore grade value amounting to several per cent. Many natural "asphaltites," however, contain little or no uranium, and spectrographic traces of uranium have not been reported to produce noticeable induration in petroleum.

The Uranian Asphaltite-Coffinite Association

The frequent association of coffinite, a uranium silicate (Stieff *et al.*, 1955, 1956) and "asphaltite" in many Colorado Plateau uranium deposits is believed to provide significant information on the temperature conditions which prevailed during uranium mineralization. Stieff *et al.* (1956) have called attention to some 40 occurrences of coffinite on the Colorado Plateau and in adjacent areas. Most of these contain associated organic material. Hydrothermal occurrences of coffinite in Colorado (Sims *et al.*, 1958), and the rather restricted hydrothermal conditions under which coffinite has been synthesized (Fuchs and Hoekstra, 1959), point to coffinite as a mineral of hydrothermal origin. The range in temperature of formation for coffinite coincides with the range in temperature at which semi-fluid asphalt becomes indurated. The similarity between the infrared absorption spectra of natural uranium-bearing "asphaltite" and asphaltite indurated by heat is an additional confirmatory factor.

Mineralogical investigation of coffinite has been carried out on material from a number of occurrences including the original coffinite from the La Sal No. 2 mine, Mesa County, Colorado kindly supplied by Dr. L. R. Stieff of the U. S. Geologic Survey; the Jackpile mine and Section 33 mine, New Mexico; the Green River district, and the Temple Mountain area, Utah.

The Separation of Coffinite

Coffinite on the Plateau is found disseminated in hard "asphaltic" material which contains uraninite and quartz as prominent impurities. Those who have investigated the mineral have found it difficult to obtain even approximately pure coffinite. As a result, the literature shows a lack of chemical analyses of the pure material necessary to provide the exact chemical composition of the mineral.

Ordinary organic solvents fail to dissolve the associated organic material, but heating to 410° C. for two to three days has been found effective in removing the organic material. However, the presence of small amounts of uraninite and other finely disseminated uranium-bearing constituents in the organic complex may still cause uncertainty in the determination of the silica-uranium ratio of coffinite.

X-ray Data on Coffinite

X-ray diffraction patterns of coffinite indicate (Stieff *et al.* 1956) that the mineral is tetragonal with a zircon type structure. *X*-ray patterns for a number of coffinite samples using copper radiation and a nickel filter are shown in Table 1. The coffinite localities represented are the Jackpile

Table 1. *X*-Ray Diffraction Powder Patterns of Coffinite
(Copper radiation, Nickel filter)

hkl	Coffinite, Jackpile mine, New Mexico		Coffinite, Green River, Utah		Coffinite, La Sal No. 2 mine, Colorado		Coffinite, Temple Mountain, Utah		Coffinite, Arrowhead mine, Colorado*		Coffinite, USSR†	
	*d*Å	I	*d*Å	I	*d*Å	I	*d*Å	I	*d*Å	I	*d*Å	I
(011)	4.668	9	4.668	9	4.643	9	4.619	10	4.66	10	4.67	9
(200)	—	—	—	—	—	—	—	—	—	—	3.86	5
(200)	3.470	10	3.477	10	3.464	10	3.470	9	3.47	10	3.51	10
(121)	2.778	4	2.786	4	2.778	4	2.78	4	2.78	4	2.814	4
(112)	2.642	7	2.646	8	2.642	7	2.64	5	2.64	7	2.665	9
(220)	2.453	2	2.460	3	2.440	2	2.46	2	2.46	1	2.455	5
(031)	2.169	2	2.174	3	2.162	3	2.169	2	2.18	4	2.189	8
(013)	1.999	1½	2.003	3	1.999	1	2.01	1	2.01	1	2.002	7
(321)	1.839	2	1.850	4	1.836	2	1.835	2	1.841	4	1.855	3
(312)	1.799	5	1.799	4	1.793	3	1.80	7	1.801	7	1.813	9
(123)	1.735	2	1.732	3	1.732	2	1.73	2	1.737	4	—	—
(400)	—	—	—	—	—	—	—	—	—	—	1.742	4
(411)	1.623	1	1.627	1	1.623	½	1.63	2	1.629	1	1.632	5
(004)	—	—	—	—	—	—	—	—	—	—	1.562	5
(420)	1.551	1	1.554	1	1.551	1	weak	—	1.556	1	—	—
(332)	1.453	1	weak	—	1.448b	1	weak	—	1.451	1	1.449	2
(024)	1.427	½	weak	—	1.431	½	weak	—	1.435	1	1.430	2

* Stieff *et al.*, (1956), ASTM card No. 8-304.
† Filipenko, Y. S. (1958). Interplaner spacings below 1.43Å are not reproduced.
b = broad.

mine, New Mexico; Green River, and Temple Mountain, Utah; the La Sal No. 2 mine, and the Arrowhead mine, Colorado (Stieff *et al.*, 1956); and an undisclosed locality in the U.S.S.R. (Filipenko, 1958). Coffinite from the Jackpile mine and the La Sal No. 2 mine give relatively good *x*-ray patterns; all the reflections reported by Stieff *et al.* (1956) are duplicated, and most of the lines are sharp. The two samples from Green River and Temple Mountain, Utah give poor *x*-ray patterns with relatively low line intensities and some lines that are merged with the background. The removal of the organic material does not improve the line intensities, although the elimination of quartz does result in a slight improvement. Thus it is likely that crystallite size rather than dilution accounts for the poor quality of the *x*-ray pattern.

Three samples of coffinite were analyzed qualitatively for heavy elements with the *x*-ray spectrograph using tungsten radiation and a lithium fluoride crystal. The elements detected are shown in Table 2. It has been observed that in the *x*-ray fluorescence curve for coffinite from the Jackpile mine, New Mexico no reflections for heavy elements other than uranium are exhibited. Since this material also gives the best *x*-ray diffraction pattern obtained from samples used in this work, it may be inferred that arsenic, lead, iron, and vanadium noted in the other two samples are probably either absent or constitute non-essential impurities.

TABLE 2. *X*-RAY SPECTROGRAPHIC ANALYSES OF COFFINITE

Coffinite, Jackpile mine, New Mexico	Coffinite, Green River, Utah	Coffinite, Section 33 mine, Grants, New Mexico
U	U	U
	As	Pb
	Fe	
	V	

THERMAL BEHAVIOR OF URANIAN ASPHALTITE AND COFFINITE

Differential thermal analysis of coffinite-bearing "asphaltite" samples from Green River, Utah and the Jackpile mine, New Mexico show a strong and broad exothermic reaction which attains a maximum at 480°–500° C. (Fig. 2, curves Nos. 1 and 2). This reaction is believed to be caused by the oxidation of associated "asphaltite." The coincidence of the temperature at which this reaction takes place and the temperature at which the coffinite lattice is destroyed in air (500° C.) is probably accidental.

Differential thermal analysis of coffinite-bearing "asphaltite" from the Jackpile mine in vacuum shows no reactions up to 1000° C. (Fig. 2, curve No. 3). "Asphaltite"-free coffinite obtained by roasting at 410° C. for three days gives no thermal reaction in air (Fig. 2, curve No. 4). The lattice destruction of coffinite at 500° C. was not accompanied by any observable thermal reaction.

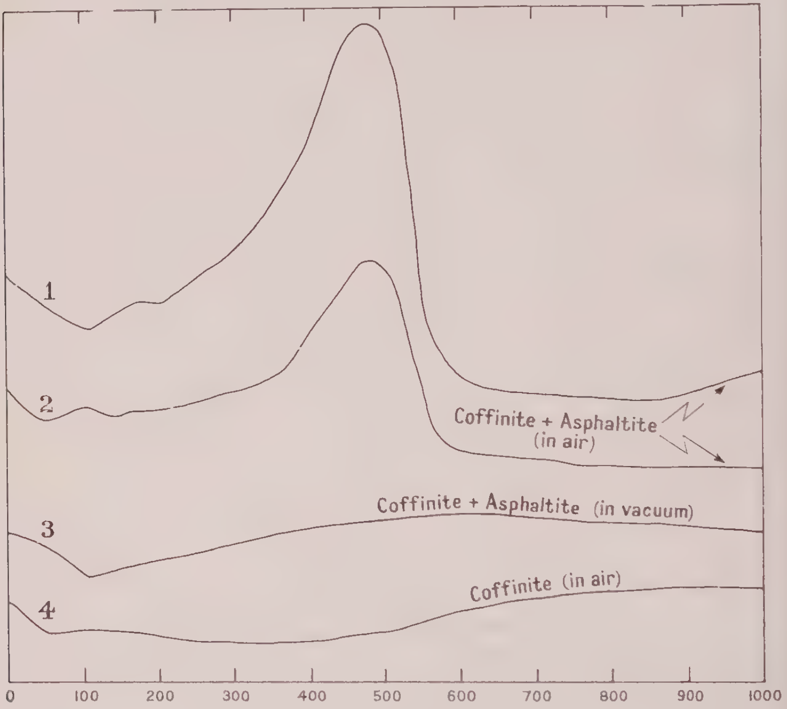

Fig. 2. D. T. A. of coffinite samples.

X-Ray Data on Heated Samples

A sample of coffinite-bearing "asphaltite" from the Jackpile mine was heated in an electric oven for two hours at each of the following temperatures. 200, 300, 400, 500, 600, 700, 840, 960 degrees centigrade, and an *x*-ray pattern was made of each product. The patterns were taken, after cooling to room temperature, using copper radiation and a nickel filter. The small amount of quartz which was present in the sample gave persistent lines throughout the temperature range. The strongest quartz line at 3.349 Å maintained approximately the same intensity in each pattern and served as a datum to which changes in the intensity of coffinite lines could be referred. Table 3 shows the first four coffinite lines with intensities based on the quartz line at 3.349 Å considered as 10.

In the interval between 200° C. and 400° C. a slight decrease occurs in the intensity of coffinite lines. There is also a slight shift of the first three lines towards lower spacing values, although the significance of this shift is uncertain. At 500° C. there is a pronounced drop in the intensity of the coffinite lines and the three strongest lines shift toward lower *d* values. At 600°–700° C. the intensity of the two strongest lines shows a further drop, and the other lines are extremely weak; also, the first line drops to 4.110, the value for the first line of U_3O_8. The strongest coffinite line drops to 3.386 Å at 840° C. It is noted that the three strongest coffinite lines 4.668 Å, 3.470 Å, and 2.642 Å shift to 4.110 Å, 3.386 Å, and 2.627 Å values respectively, which correspond to the three strongest lines of the pattern for U_3O_8. At 840° C. the intensities of the U_3O_8 lines increase and some additional lines are developed. At 960° C. the pattern developed agrees with U_3O_8. Gruner and Smith (1955) report that cof-

TABLE 3. *X*-RAY DIFFRACTION OF COFFINITE HEATED IN AIR

(Jackpile mine, New Mexico)

Intensities computed taking strongest quartz line 10

Cu/Ni Radiation

Unheated		200°–400° C.		500° C.		600° C.	
*d*Å	I	*d*Å	I	*d*Å	I	*d*Å	I
4.668	9	4.619	8	4.595	$2\frac{1}{2}$	4.595	1
3.470	10	3.437	9	3.424	3	3.386	1
3.349*	10	3.336*	10	3.349*	10	3.349*	10
2.778	4	2.761	3	2.761	$1\frac{1}{2}$	very weak	
2.642	6	2.642	5	2.627	$1\frac{1}{2}$	very weak	

700° C.		840° C.		960° C.		U_3O_8†	
*d*Å	I	*d*Å	I	*d*Å	I	*d*Å	I
4.110	1	4.110	7	4.110	8	4.110	4
3.386	1	3.386	8	3.386	6	3.390	10
3.349*	10	3.349*	10	3.349*	10		
2.627	1	2.627b	7	2.627	6	2.62	7
very weak lines		2.069	1	2.074	1	2.06	3

* Strongest α-quartz line.

† Milne (1951); ASTM card No. 4-0511.

b = broad.

finite showed some decrease in cell dimensions when heated in air at 500° C., while virtual destruction of the lattice occurred at 600° C. Fuchs and Hoekstra (1959) place the stability limits for synthetic coffinite at 500° C. in air and 1000° C. in vacuum.

In summary, the three strongest coffinite lines decrease sharply in intensity at 500° C. and show some shift toward the spacings of the three strongest U_3O_8 lines. The shift in spacing toward U_3O_8 lines is completed by 840° C. and is accompanied by an increase in line intensities and definition.

Loss of Weight and Change in Color

In a further attempt to investigate the nature of the reactions shown in the D. T. A. of coffinite-bearing "asphaltite," a dried sample from the Jackpile mine, New Mexico was heated in an electric oven for one hour at each of the following temperatures: 110, 200, 300, 400, 500, 600, 700, and 960 degrees centigrade. After each heating the sample was weighed on a sensitive balance after allowing to cool in a desiccator to room temperature. Up to 400° C. (Fig. 3) the loss of weight amounts to only two per cent of the weight at 110° C. Between 400° C. and 500° C. a sharp drop in weight occurs. The weight at this temperature is found to be 33.3 per cent of the weight at 110° C. From 500° C. to 960° C. the weight

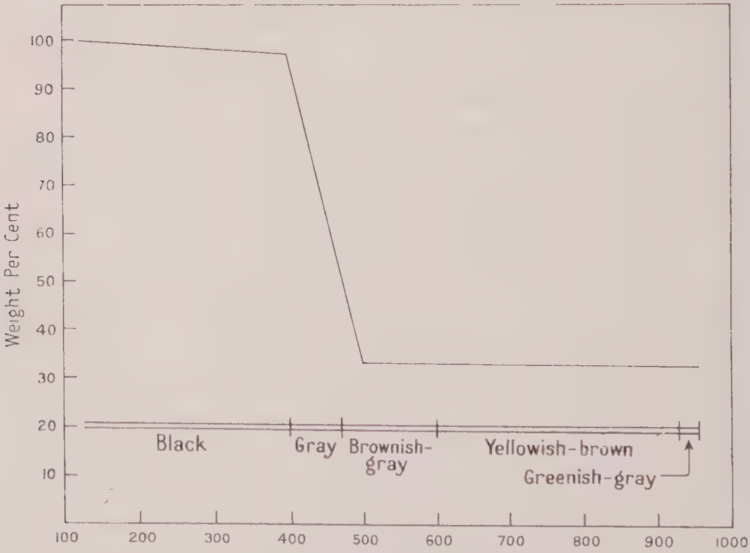

FIG. 3. Heat effects on weight and color of coffinite.

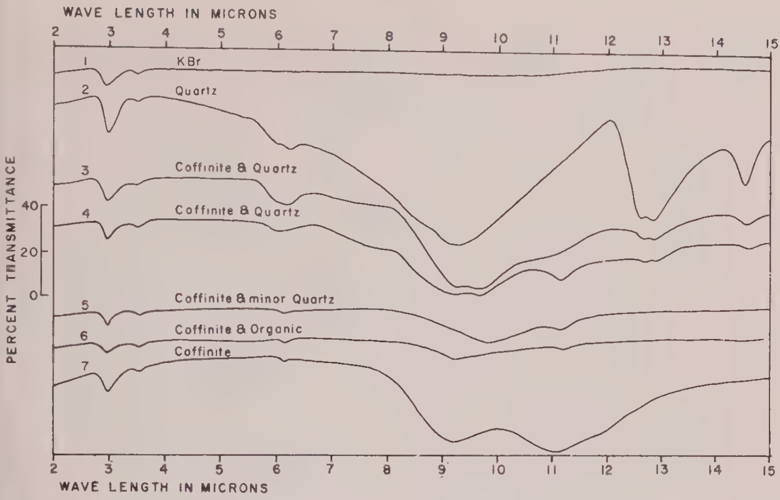

FIG. 4. Infrared absorption of coffinite.

essentially stable, the final weight per cent of the sample at 960° C. eing 33.28. Coffinite-bearing "asphaltite" from La Sal No. 2 mine lost 3 per cent of its weight on heating in air at 410° C. for two days. The ss of weight is accompanied by the evolution of CO_2 and H_2O caused y the oxidation of the organic material.

Color changes in coffinite-bearing samples have been observed (Fig. 3) fter several stages of heating. Up to 400° C. it remains black. Between 00° C. an 500° C. a rapid change is observed from black to gray to rownish-gray. At 600° C. it becomes yellowish-brown and retains this olor until it becomes greenish-gray at 960° C. Similar color changes ere observed by Stieff *et al.* (1956).

INFRARED ABSORPTION OF HEAT TREATED SAMPLES

Coffinite samples from the Jackpile mine and La Sal No. 2 mine were elected for infrared absorption study (Fig. 4). Curves were obtained oth for samples containing organic material and for samples heated at 10° C. for two days to eliminate organic material.

The organic-free samples showed stronger silica absorption bands han samples contaminated with organic material as may be observed by omparing curves No. 6 and No. 7 (Fig. 4). Curve No. 6 represents or-anic material bearing coffinite from La Sal No. 2 mine; it shows two weak silica absorption bands near 9 and 11 microns. Increasing the hickness of the sample increases the opacity of the pellet and fails to improve the absorption curves. Curve No. 7 represents coffinite from La Sal No. 2 mine free from the organic material; it shows two distinct and strong bands near 9 and 11 microns. Curve No. 6 is similar to a previously published curve of coffinite from the same locality by Stieff *et al.* (1956, Fig. 1, p. 687).

In a discussion of infrared absorption by the SiO_4 group, Eitel (1954, p. 17) concludes that the active inner characteristic vibrations of the SiO_4 group ($\lambda = 10–12\ \mu$) takes place at shorter wave lengths with increasing interlinkage of the SiO_4 tetrahedra. Quartz has a framework structure with a maximum interlinkage between the silica tetrahedra groups and shows a strong absorption band which attains a maximum at 9.3 (quartz from Herkimer County, New York, Fig. 4, curve No. 2).

Quartz-free coffinite from the La Sal No. 2 mine shows an absorption band which attains a maximum at 9.2 μ corresponding to that of quartz. In addition, coffinite shows an absorption band at 11–11.2 μ indicating isolated tetrahedra (Launer, 1952).

The presence of a moderate amount of quartz as an impurity in coffinite causes an overlap of the 9–10 μ silica bands for the two minerals which results in a broadening of the silica absorption in this region. This broadening effect tends to impair the resolution of the 11 μ band of coffinite which often shows as a flexure rather than as a distinct band (Fig. 4, curve No. 3). Progressive removal of quartz causes a pronounced decrease in the intentisy of the 9–10 μ band and the appearance of a distinct band near 11 μ characteristic of isolated silica tetrahedra (Fig. 4, curves No. 4 and 5). Quartz shows two additional bands at 12.5–12.8 μ and 14.5 μ but these do not appear in quartz-free coffinite.

The infrared absorption study of silica in coffinite points to agreement with the conclusion of Stieff *et al.* (1956) on natural coffinite and with Fuchs and Hoekstra (1959) on synthetic coffinite that the mineral has isolated silica tetrahedra in its structure.

Coffinite shows a rather broad O-H absorption band which attains a maximum at 2.95 μ with a weak band at 3.5 μ. These two bands also appear in KBr blanks and quartz. Prolonged pressure at 200° C. results in the virtual disappearance of the bands for the KBr blanks, but does not eliminate them from either quartz or coffinite samples.

A coffinite sample dried at 410° C. and another heated in air at 750° C. for two days to insure the destruction of the coffinite lattice shows no difference in the 2.95 μ band. This indicates that the 2.95 μ band is probably caused by absorbed water rather than by an (O-H) group in the coffinite lattice.

According to Keller and Pickett (1949) monomeric (O-H) within a crystal lattice absorbs at 2.75 μ, dimeric bonded (O-H) groups absorb at 2.85 μ, and polymeric (O-H) groups absorb at 2.95 μ. The O-H absorption of coffinite appears at 2.95 μ, is absent at 2.75 μ, and the slope of the absorption curve does not show any interruption at 2.85 μ. This indicates that the 2.95 μ band is caused by polymeric (O-H) groups caused probably by absorbed water. Water in the H_2O form absorbs in the 2.8 μ and 6.1 μ region, and therefore infrared absorption spectra do not distinguish between mechanically trapped H_2O and H_2O which forms an integral part of the crystal as in gypsum or hydrogen bonded water (Keller and Pickett, 1954, p. 90).

A KBr disc, slightly thicker than the sample disc, placed in the path of the standard infrared ray of a split beam recorder produces a negative H_2O absorption band without any interruption in the 2.8–2.95 μ slope, indicating the absence of monomeric and dimeric (O-H) groups and also indicating that the absorption band in this region is caused by absorbed water. The absence of thermal reactions of coffinite free from organic material up to 1000° C. indicates the absence of the (O-H) group from the coffinite lattice. Fuchs and Hoekstra (1959) found that synthetic coffinite does not show any change in cell dimensions or line intensities for material heated to 1000° C. in vacuum and concluded that synthetic coffinite is $USiO_4$ without an essential hydroxyl component.

Natural coffinite specimens from the Jackpile mine and La Sal No. 2 mine are believed to have no essential hydroxyl component in the structure and in this respect are similar to synthetic coffinite.

Chemical analyses of natural coffinite (Stieff *et al.*, 1956) show a lower silica content than would be stoichiometrically proportional to uranium in the formula $USiO_4$ and have been considered to indicate a hydroxyl substitution of silica. However, Stieff *et al.* did not exclude the possibility that unseparated uranium oxide might account for the silica-uranium ratio discrepancy.

OPTICAL OBSERVATIONS

Under the microscope the black asphaltic material is opaque except in small fragments where it is translucent dark brown. "Asphaltite"-free coffinite obtained by heating at 410° C. for three days consists of a mixture of coffinite aggregates and quartz. Coffinite is isotropic, transparent greenish-yellow in small fragments and mottled translucent brown in thick aggregates. Intergrowth of coffinite with quartz and possibly surface replacement of the latter may be observed in many grains. The replaced surfaces of the quartz grains show parallel striations suggesting preferred orientation of replacement parallel to the *c*-axis of quartz. The precipitation of quartz with synthetic coffinite was observed by Fuchs and Hoekstra (1959), and coffinite from the Soviet Union has been reported (Filipenko, 1958) to be associated with quartz.

ELECTRON MICROGRAPHS

Small portions of "asphaltite"-free and quartz-free coffinite from the Jackpile mine were optically examined and then ground to minus 350 mesh after which suspensions in collodion films were prepared for observation under the electron microscope. Aggregates of coffinite appear almost opaque on the screen, but a tracing of the aggregate outlines taken from several electron photomicrographs indicates crystal boundaries (Fig. 5).

FIG. 5. Crystal outlines of coffinite aggregates, traced from electron photomicrographs.

COFFINITE AS AN INDICATOR OF HYDROTHERMAL ORIGIN

Descriptions of occurrences and synthesis suggest that coffinite is worthy of consideration as a temperature indicator for Colorado Plateau uranium deposits.

Coffinite has been reported (Sims *et al.*, 1958) associated with uraninite in the Copper King uranium mine, Larimer County, Colorado. The mine occurs near the central part of a Precambrian batholith of Silver Plume granite known as the Log Cabin batholith. Coffinite and uraninite occur along the Copper King fault and are associated with a hydrothermal assemblage of vein-forming minerals such as siderite, pyrite, marcasite, quartz, sphalerite, chalcopyrite, and magnetite.

In the Soviet Union coffinite has been found (Filipenko, 1958) in fissures in granite, It occurs in the form of thin lenses and irregularly shaped nests associated with pyrite, galena, and chalcopyrite, as well as quartz and several disintegration products of feldspars such as sericite and kaolinite.

Fuchs and Hoekstra (1959) synthesized coffinite by a hydrothermal procedure. They indicate that depolymerization of the polysilicate and the formation of $USiO_4$ occurs during the heating process rather than during the precipitation step and report that co-precipitation of uranium and silica is necessary for coffinite synthesis. They also state that coffinite is not likely to form in nature by the reaction of finely divided UO_2 and colloidal silica. Reducing and alkaline environment were found to be essential to the formation of coffinite and the temperature limits are set at 200° C. to 360° C.

CONCLUSIONS

The widespread urano-organic association in hydrothermal deposits suggests a hydrothermal source for the original uranium ions of the Colorado Plateau deposits.

Liquid hydrocarbons from the San Rafael Swell may be indurated under conditions of elevated temperature in the range between 200° C. and 300° C. The heated products give infrared curves similar to natural uranium-bearing "asphaltites" suggesting that the natural material could have been hardened by the action of hydrothermal solutions. Polymerization caused by irradiation is recognized as a possible originating mechanism for materials of high radioactivity. However, indurated "asphaltites" low in radioactivity are abundant, and their physical condition is better accounted for by the action of heat derived from hydrothermal solutions barren of uranium.

Infrared, *x*-ray, and D. T. A. study of coffinite indicates that the mineral is a uranium silicate without an essential hydroxyl component. Hydrothermal occurrences of coffinite and the temperature of its synthesis suggest a special significance as a temperature indicator.

The intimate coffinite-"asphaltite" association is not conceivable as a product of irradiation; at the same time, the uranium silicate is a likely product of hydrothermal action.

ACKNOWLEDGMENTS

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REFERENCES

BOWIE, S. H. U., 1955, Thucholite and hisingerite-pitchblende complexes from Nicholson mine, Saskatchewan, Canada: *Gr. Britain Geol. Sur., Bull* **10,** 45–57.

BREGER, I. A., AND DEUL, M., 1955, The association of uranium with carbonaceous materials on the Colorado Plateau: *U. S. Atomic Energy Commission, TEIR*-**539,** 1–35.

——— 1956, The organic geochemistry of uranium: *United Nations Conference on Peaceful Uses of Atomic Energy, Proc.*, **6,** 418–421.

CHRISTIE, A. M., AND KESTON, S. N., 1949, Goldqelds and Martin Lake Map-Areas, Saskatchewan: *Geol. Sur. Canada, Paper* **49,** 17 pp.

DAVIDSON, C. F., AND BOWIE, S. H. U., 1951, On thucholite and related hydrocarbon-uraninite complexes: *Gt. Britain Geol. Sur. Bull.* **3,** 1–19.

DAVIDSON, C. F., 1955, Concentration of uranium by carbon compounds: *Econ. Geol.*, **50,** 879–880.

EITEL, W., 1954, The Physical Chemistry of the Silicates: The University of Chicago Press, 1592 pp.

ELSWORTH, R. V., 1928, Thucholite from the vicinity of Parry Sound, Ontario: *Am. Mineral.*, **13,** 419–442.

ERICKSON, R. L., MYERS, A. T., AND HORR, C. A., 1954, Association of uranium and other metals with crude oil, asphalt, and petroliferous rock: *Am. Assoc. Petrol. Geol. Bull.*, **38,** 2200–2218.

FILIPENKO, Y. S., 1958, "Coffinite," In: New data on uranium minerals in the USSR; *United Nations Second Conference on Peaceful Uses of Atomic Energy, Proc.*, **2,** 302–304.

FUCHS, L. H., AND HOEKSTRA, H. R., 1959, Preparations and properties of uranium (IV) silicate: *Am. Mineral.*, **44,** 1057–1063.

GOTT, G. B., AND ERICKSON, R. L., 1952, Reconnaissance of Uranium and Copper Deposits in Parts of New Mexico, Colorado, Utah, Idaho, and Wyoming: *U. S. Geol. Sur. Circ.* **219,** 16 pp.

GRUNER, J. W., AND SMITH, D. K., JR., 1955, Annual Report for April 1, 1954 to March 31, 1955 *U. S. Atomic Energy Commission, RME*-**3020,** 37 pp.

HAIL, W. J., MYERS, A. T., AND HORR, C. A., 1956, Uranium in asphalt-bearing rocks: *United Nations Conference on Peaceful Uses of Atomic Energy, Proc.*, **6,** 489–493.

HUNT, J. M., STEWART, F., AND DICKEY, P. A., 1954, Origin of hydrocarbons of Unita basin, Utah: *Am. Assoc. Petrol. Geol. Bull.* **38,** 1671–1698.

HYDEN, H. J., 1956, Uranium and other trace metals in crude oils of the western United States: U. S. Geol. Sur. Prof. Paper **300,** 511–519.

ISACHSEN, Y. W., AND EVENSEN, C. G., 1956, Geology of uranium deposits of the Shinarump and Chinle formations on the Colorado Plateau: *U. S. Geol. Sur. Prof. Paper*, **300,** 263–280.

KELLER, W. D., AND PICKETT, E. E., 1949, Absorption of infrared radiation by powdered silica minerals: *Am. Mineral.*, **34,** 855–868.

——— 1954, Hydroxyl and water in perlite from Superior, Arizona: *Am. J. Sci.*, **252,** 87–98.

KELLEY, D. R., AND KERR, P. F., 1958, Urano-organic ore at Temple Mountain, Utah: *Geol. Soc. Am. Bull.*, **69,** 701–756.

LAUNER, P. J., 1952, Regularities in the infrared absorption of silicate minerals: *Am. Mineral.*, **37** 764–784.

inares, E., 1956, The "Eva Peron" deposit, Malargue, Mendoza: *United Nations Conference on Peaceful Uses of Atomic Energy, Proc.*, **6,** 75–81.

awson, Sir Douglas, 1944, The nature and occurrence of uraniferous mineral deposits in South Australia: *Trans. Roy. Soc. S. Australia*, **68,** 334–357.

cKelvey, V. E., Everhart, D. L., and Garrels, R. M., 1956, Summary of hypotheses of genesis of uranium deposits: *United Nations Conference on Peaceful Uses of Atomic Energy, Proc.*, **6,** 551–561.

ierce, A. P., Mytton, J. W., and Barnett, P. R., 1958, Geochemistry of uranium in organic substances in petroliferous rocks: *United Nations Second Conference on Peaceful Uses of Atomic Energy, Proc.*, **2,** 192–198.

ims, P. K., Phair, G., and Moench, R. H., 1958, Geology of the Copper King uranium mine, Larimer County, Colorado: U. S. Geol. Sur. Bull. **1032**-*D*, 171–221.

pence, H. S., 1930 A remarkable occurrence of thucholite and oil in a pegmatite dyke, Parry Sound, Ontario: *Am. Mineral.*, **15,** 499–520.

tieff, L. R., Stern, T. W., and Sherwood, A. M., 1955, Preliminary description of coffinite—a new uranium mineral: *Science*, **121,** 608–609.

——— 1956, Coffinite, a uranous silicate with hydroxyl substitution: a uranium mineral: *Am. Mineral.*, **41,** 675–688.

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NORSETHITE, $BaMg(CO_3)_2$, A NEW MINERAL FROM THE GREEN RIVER FORMATION, WYOMING*

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ABSTRACT

Norsethite, $BaMg(CO_3)_2$, was found in dolomitic black oil shale below the main trona bed in the Westvaco trona mine in Wyoming, associated with shortite, labuntsovite, searlesite, loughlinite, pyrite, and quartz. It also occurs there in gray shale with abundant shortite and northupite, some searlesite and loughlinite, in a fine-grained matrix consisting essentially of quartz and pyrite.

Norsethite occurs as clear to milky-white circular plates or flattened rhombohedral crystals, 0.2–2.0 mm. across. The mineral is insoluble in water but is readily decomposed by cold dilute hydrochloric acid. Norsethite has hardness about 3.5; density 3.837 ± 0.005 (meas.), 3.840 (calc.); luster vitreous to pearly; fracture hackly; good rhombohedral cleavage. It is infusible before the blowpipe. Norsethite is uniaxial negative, and the indices of refraction are $\omega = 1.694$ and $\epsilon = 1.519$. *X*-ray crystallographic studies show that the crystals are rhombohedral and have the following characteristics: possible space groups, $R\bar{3}m$, $R3m$, or $R32$, the most probable being $R32$ (D_3^7), a subgroup of $R\bar{3}c$, the space group of calcite; hexagonal $a = 5.020 \pm 0.005$ Å, $c = 16.75 \pm 0.02$; rhombohedral $a_{rh} = 6.29 \pm 0.01$ Å, $\alpha = 47°02' \pm 05'$; volume 365.6 Å^3 (hex.); cell contents: $3[BaMg(CO_3)_2]$, in the hexagonal unit. Crystal forms observed are $c\{10001\}$, $a\ \{11\bar{2}0\}$, $m\ \{1010\}$, and $r\ \{10\bar{1}1\}$. The strongest *x*-ray lines are: 3.015 Å (100), 3.860 (35), 2.656 (35), 2.512 (35), 2.104 (35), 1.931 (35), 1.864 (35).

Norsethite has a structure similar to that of calcite. The structural relations of norsethite, dolomite, and calcite are discussed.

Chemical analysis of a 0.1 gm. sample gave: BaO 52.9, CaO 0.5, MgO 13.9, FeO 0.4, MnO 0.1, CO_2 31.2, Na_2O 0.2, SiO_2 0.3, insoluble 0.4, total 99.9 per cent.

Norsethite is named in honor of Mr. Keith Norseth, engineering geologist of the trona mine at Westvaco, Sweetwater County, Wyoming.

INTRODUCTION

The new mineral norsethite, $BaMg(CO_3)_2$, was discovered during the investigation of the authigenic minerals of the Green River formation of Wyoming, Utah, and Colorado. It occurs in microscopic quantities at the Westvaco trona mine which is about 18 miles west of Green River, Wyoming. So far, norsethite has not been found at any other Green River locality.

The specimens that contained the crystals of norsethite were collected by Charles Milton who first observed this new mineral and named it in honor of Mr. Keith Norseth, engineering geologist at the Westvaco trona mine, in grateful acknowledgment of his friendly assistance in the mineralogical studies of these authigenic minerals.

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* Publication authorized by the Director, U. S. Geological Survey.

Occurrence of Norsethite

Norsethite first was observed as clear to milky-white plates flattened parallel to the basal pinacoid (Figs. 1 and 4) in the dolomitic black oil shale which underlies the main trona bed at the Westvaco trona mine in Wyoming. There the mineral has been found associated with shortite [$Na_2Ca_2(CO_3)_3$], labuntsovite [$(Na,K)_2(Ba,Mg)(Ti,Al,Fe,Nb)_2Si_4O_{11}(OH)_6$], searlesite [$NaBSi_2O_6 \cdot H_2O$], loughlinite [$Na_2Mg_3Si_6O_{16} \cdot 8H_2O$], pyrite, and quartz. Norsethite also occurs at the Westvaco mine in a gray shale that consists largely of quartz and a small amount of pyrite; the associated minerals are abundant shortite and northupite [$Na_3MgCl(CO_3)_2$], and lesser amounts of searlesite and loughlinite. The water-insoluble residue of trona core from an unknown depth, drilled in the area of the Westvaco trona mine, yielded discoid masses of norsethite (Fig. 2). In addition, good crystals of the type shown in Figs. 1 and 3 were obtained from the waste sodium-carbonate "mud" discharged from the soda-ash processing plant at Westvaco, along with pyrite, shortite, dolomite, calcite, labuntsovite, barytocalcite [$CaBa(CO_3)_2$], leucosphenite [$Na_3CaBaBTi_3Si_9O_{29}$], and witherite [$BaCO_3$].

Thus far, norsethite has not been found in the dolomitic oil shales of Utah or Colorado.

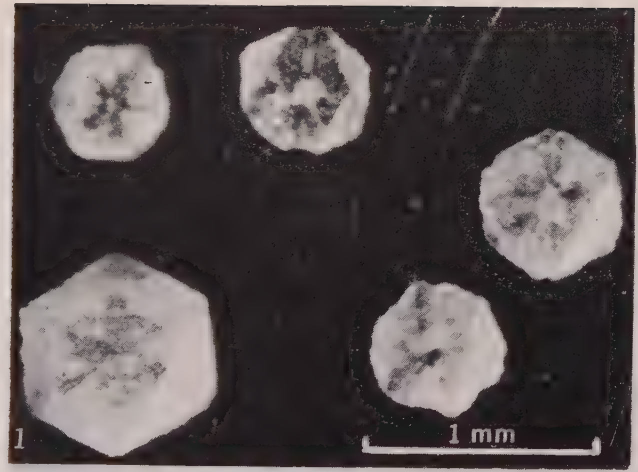
Mineral Separation

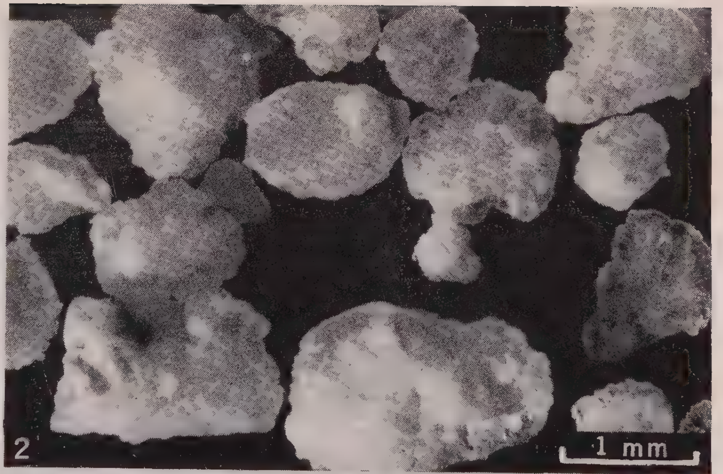
Norsethite crystals were isolated from the rock specimens, the trona core, and the waste sodium-carbonate "mud" by heavy-liquid separation (bromoform), followed by hand-picking under the binocular microscope. Associated with norsethite in the waste "mud" were crystals of barytocalcite and witherite, nearly identical in habit with those of norsethite. Norsethite could not be distinguished readily from barytocalcite and witherite by means of indices of refraction, or by specific gravity, since Clerici solution attacks carbonates. It was necessary to check each individual crystal of such habits under the microscope; norsethite is uniaxial negative, whereas barytocalcite and witherite are both biaxial negative with small 2V.

The material submitted for the chemical analysis (0.1 gm.) was obtained from a single specimen of dolomitic shale which was free from barytocalcite and witherite. In this instance only bromoform separation was required.

Physical and Optical Properties

Norsethite occurs as clear to milky-white circular plates or flattened rhombohedral crystals with diameters ranging from 0.2 to 2.0 mm. (Figs. 1–4). Some crystals, as well as irregular grains, show corrugated


1
1 mm


2
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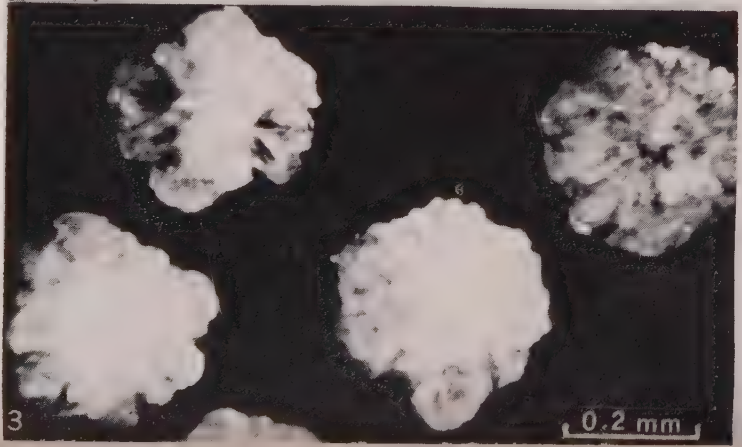
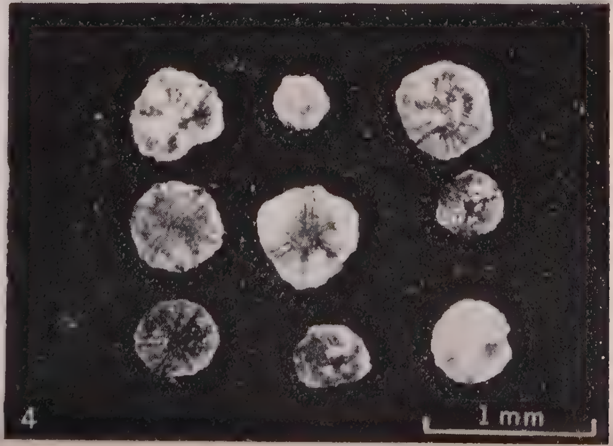

3
0.2 mm


4
1 mm

flattened edges; the thick corrugated grains are pumpkin-shaped. he mineral has a vitreous luster, a hackly fracture, and good rhomboedral cleavage $\{10\bar{1}1\}$. Its hardness is about 3.5. Norsethite is insoluble water but is readily decomposed by cold dilute hydrochloric acid. It infusible before the blowpipe. The specific gravity, determined on nall crystals of norsethite on the Berman microbalance, using toluene the immersion liquid, is 3.837±0.005 (an average of six different derminations); for large crystals, 3.810±0.005; the calculated specific avity is 3.840. Most of the crystals of norsethite that were examined

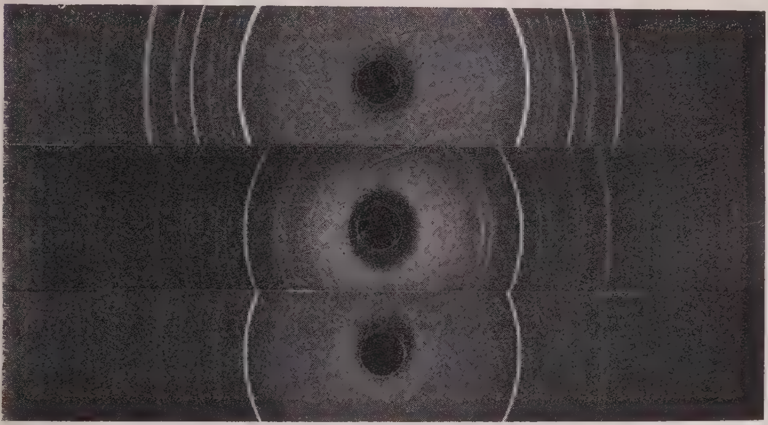


Fig. 5. *X*-ray powder photographs (Cu Kα radiation). (above) Calcite, Westvaco trona ne, Sweetwater County, Wyoming. (middle) Norsethite, Westvaco trona mine. (below) lomite, Binnental, Switzerland.

der the microscope showed fluid inclusions or cavities; some appear as annels normal to, and in between, the rhombohedral faces, as shown in g. 1 and 4. The presence of cavities and channels in the large crystals doubtedly accounts for the difference between the observed and calcued values.

Optically, norsethite is uniaxial negative. The mineral is colorless in nsmitted light. The indices of refraction were determined by the imrsion method using sodium light and were corrected to 25° C. The or of measurement probably is not greater than ±0.001; $\omega=1.694$ d $\epsilon=1.519$; $\Delta=0.175$ (Na).

The rule of Gladstone and Dale $[(n-1)/d=K]$ was found to hold rprisingly well for norsethite. Norsethite with $d=3.837$ (meas.) and $=0.16632$ (based on the recalculated chemical analysis in Table 3) es $dK+1=1.638$ for the calculated mean index and $(2\omega+\epsilon)/3=1.636$ the measured mean index.

CRYSTALLOGRAPHY

Morphology

The faces on the well-formed crystals of norsethite gave only fair signals on the optical goniometer. The forms observed were identified readily from goniometric measurements correlated with the single-crystal *x*-ray results. The morphology of the largest crystals measured (averaging 1.0 mm. in diameter) consists only of a well-developed base $\{0001\}$ and the rhombohedron $\{10\bar{1}1\}$. The small crystals (less than 0.5 mm. in diameter) showed, in addition, the first order prism $\{10\bar{1}0\}$ and the second order prism $\{11\bar{2}0\}$, as very narrow faces.

The notable absence of a bipyramidal form on any of the numerous crystals examined made it impossible to determine the crystal class from morphological considerations alone. The crystals are holohedral in habit. They gave no positive piezoelectric response on the Giebe-Scheibe apparatus. This evidence would suggest that the crystal class is either rhombohedral ($\bar{3}$) or scalenohedral ($\bar{3}2/m$). Both these possibilities were eliminated and the crystal class was established as trigonal-trapezohedral (32) from a consideration of the space group criteria and the structural relation of norsethite to calcite (see discussion on page 426).

X-ray powder data

An *x*-ray powder diffraction pattern of norsethite (film no. 11793) was taken in a 114.59 mm. diameter Debye-Scherrer camera with nickel-filtered copper radiation ($\lambda = 1.5418$ Å), using both the Straumanis and Wilson techniques (Fig. 5). Film measurements were corrected for shrinkage. All interplanar spacings and intensities for the observed lines are given in Table 1, column 2. The intensities were estimated visually by comparison with a calibrated intensity strip. Interplanar spacings were calculated from the *x*-ray cell constants down to a value of $d_{hk \cdot l} = 1.005$ Å on a digital computer using a program developed and carried out by Daniel E. Appleman. All calculated spacings for $d_{hk \cdot l} \geq 1.000$ Å for norsethite are listed in Table 1, column 1.

Single-crystal x-ray data

A thin, tabular, hexagonal-shaped crystal of norsethite (approximately 0.5 mm. in diameter) was examined by the Buerger precession method. A quartz-calibrated precession camera was used with zirconium-filtered molybdenum radiation ($\lambda = 0.7107$ Å) to obtain the $h0 \cdot l$, $h1 \cdot l$, $hk \cdot 0$, $hk \cdot 1$, and $hh \cdot l$ net planes. These photographs established the lattice as rhombohedral and, together with the film measurements (corrected for horizontal and vertical shrinkage), led to the crystallographic data given in Table 2.

TABLE 1. COMPARISON OF X-RAY POWDER DATA FOR NORSETHITE, DOLOMITE, AND CALCITE

Norsethite, $BaMg(CO_3)_2$ Westvaco trona mine, Sweetwater Co., Wyoming Present Study				Dolomite, $CaMg(CO_3)_2$ Ross Township, Haley, Ontario Howie and Broadhurst, 1958		Calcite, $CaCO_3$ Synthetic Swanson and Fuyat, 1953	
(1) Calculated[a]		(2) Measured[b]		(3) Measured[c]		(4) Measured[d]	
hk.l	$d_{hk.l}$	$d_{hk.l}$	I	$d_{hk.l}$	I	$d_{hk.l}$	I
00.3	5.583	5.584	25				
10.1	4.208	4.210	30	4.025	3		
01.2	3.859	3.860	35	3.690	5	3.86	12
10.4	3.016	3.015	100	2.886	100	3.035	100
00.6	2.792	2.795	3	2.670	10	2.845	3
01.5	2.654	2.656	35	2.540	8		
11.0	2.510	2.512	35	2.405	10	2.495	14
11.3	2.289	2.290	25	2.192	30	2.285	18
02.1	2.156	2.154	25	2.066	15		
20.2 10.7	2.104 2.096	2.104	35	2.015	15	2.095	18
02.4	1.929	1.931	35	1.848	5	1.927	5
01.8	1.886	1.890	25	1.804	20	1.913	17
11.6 00.9	1.867 1.861	1.864	35	1.786 1.781	30	1.875	17
20.5	1.824	1.824	3				
21.1	1.635	1.636	6	1.567	8	1.626	4
12.2 02.7	1.612 1.609	1.612	18				
10.10	1.563	1.563	6	1.496	2	1.587	2
21.4	1.530	1.530	25	1.465	5	1.525	5
20.8	1.508	1.510	6	1.445	4	1.518	4
11.9	1.495	1.496	6	1.431	10	1.510	3
12.5	1.475	1.475	9	1.413	4	1.473	2
03.0	1.449	1.448	9	1.389	15	1.440	5
01.11	1.437	1.437	2				
03.3 30.3	1.403	1.404	6				
00.12	1.396	1.398	6	1.335	8	1.422	3
21.7	1.355	1.356	9	1.297	4	1.356	1
02.10	1.327	1.328	9	1.269	4	1.339	2
12.8	1.293	1.295	9	1.238	5	1.297	2
03.6 30.6	1.286	1.286	9			1.284	1
22.0	1.255	1.256	6	1.202	3	1.247	1
20.11	1.247	1.248	4				
10.13	1.235	1.237	3				
22.3 11.12	1.224 1.220	1.222	9	1.168	4	1.235	2
13.1	1.203	1.203	3				

[a] Calculated from cell data for norsethite given in Table 2.

[b] Film corrected for shrinkage. Camera diameter, 114.59 mm. CuK_α radiation, Ni ter ($\lambda = 1.5418$ Å). Lower limit 2θ measurable, approximately 7.0° (12.6 Å).

[c] Powder data obtained on diffractometer with CuK_α radiation.

[d] Pattern made with a high-angle Geiger-counter spectrometer, using a sample of ceptionally high purity. CuK_α radiation ($\lambda = 1.5404$ Å at 26° C.).

(Continued on next page)

TABLE 1 (*Continued*)

Norsethite, $BaMg(CO_3)_2$ Westvaco trona mine, Sweetwater Co., Wyoming Present Study				Dolomite, $CaMg(CO_3)_2$ Ross Township, Haley, Ontario Howie and Broadhurst, 1958		Calcite, $CaCO_3$ Synthetic Swanson and Fuyat, 1953	
(1) Calculated[a]		(2) Measured[b]		(3) Measured[c]		(4) Measured[d]	
hk.l	$d_{hk.l}$	$d_{hk.l}$	I	$d_{hk.l}$	I	$d_{hk.l}$	I
31.2	1.193	1.193	4	1.144	2		
21.10	1.173	1.173	4	1.123	5	1.1795	3
13.4	1.159	1.160	9	—*		1.1538	3
01.4	1.154	1.154	3				
22.6 03.9 30.9	1.145 1.144 1.144	1.144	4	1.096	3		
31.5	1.135	1.135	6				
00.15 12.11	1.117	1.119	3	1.068	1	1.1244	<1
02.13	1.108	1.108	3				
40.1	1.084	1.086	3				
04.2 13.7	1.078 1.077	1.077	6				
40.4	1.052	1.051	3	1.008	4	1.0473	3
20.14	1.048	1.046	6			1.0613	1
31.8 22.9	1.042 1.041	1.042	3	1.001	5	1.0447	4
04.5	1.034	1.033	3				
11.15	1 020	1.020	4				
10.16 21.13	1.018 1.014	1.015	3	0.973_5	3	1.0352 1.0234	2 <1
03.12 30.12	1.005	1.006	6	0.962	5	1.0118	2
		0.9893	3	0.949	1	0.9895	<1
		0.9799	3	0.930	1	0.9846	1
		0.9717	6	0 926	3	0.9782	1
		0.9683	6	0.923	3	0.9767	3
		0.9559	3	0.913	1	0.9655	2
		0.9499	3	0.909	2		
		0.9469	3	0.903	1		
		0.9343	4	0.894	2		
		0.9223	3	0.835	4		
		0.9117	3	0.821	2		
		0.9017	4				
		0.8989	6				
		0.8961	3				

* This line was obscured by a line of the Si standard.

Structural relation to calcite and dolomite

A search of *Crystal Data* (Donnay and Nowacki, 1954) showed that dolomite [$CaMg(CO_3)_2$] and calcite [$CaCO_3$] have c/a ratios remarkably close to that of norsethite [$BaMg(CO_3)_2$]. This, coupled with the fact that these three minerals have remarkably similar crystallographic data (Table 2) as well as physical and optical properties, strongly suggested that norsethite must be a member of the same structure group as dolomite and calcite. Comparison of the *x*-ray powder films (Fig. 5) and the powder diffraction data (Table 1) for the three minerals indicated a strong structural resemblance between norsethite and calcite (space group $R\bar{3}c$), and between norsethite and dolomite (space group $R\bar{3}$).

The Buerger precession photographs of norsethite indicated only three possible space groups for the mineral: $R\bar{3}m$, $R3m$, or $R32$. Neither $R\bar{3}m$ nor $R3m$ is a possible sub-group of $R\bar{3}c$ or of $R\bar{3}$. Since evidence indicates that norsethite has a structure similar to that of calcite, and since $R32$ is the only one of the three possible space groups for norsethite which is listed as a sub-group of $R\bar{3}c$ (the space group of calcite), it follows that the space group of norsethite must be $R32$.

In order to elucidate the relation of the norsethite structure to the calcite and dolomite structures, a determination of the structure of norsethite has been undertaken and will be published in detail at a later date.

Table 2. Comparison of Crystallographic Data for Norsethite, Dolomite, and Calcite

Mineral	Norsethite	Dolomite	Calcite
Locality	Westvaco mine, Sweetwater Co., Wyoming	Ross Township, Haley, Ontario	Synthetic
Reference	Present Study	Howie and Broadhurst, 1958	Swanson and Fuyat, 1953
Symmetry	Hexagonal-R; trapezohedral-32	Hexagonal-R; rhombohedral-$\bar{3}$	Hexagonal-R; scalenohedral-$\bar{3}2/m$
Cell Constants			
a	5.020 ± 0.005 Å	4.810 ± 0.002 Å	4.989 Å
c	16.75 ± 0.02	16.02 ± 0.001	17.062
c/a	3.337	3.330	3.420
a_{rh}	6.29 ± 0.01 Å	6.020 Å	6.375 Å
α	$47°02' \pm 05'$	$47°07'$	$46°04'$
Space Group	$R32$	$R\bar{3}$	$R\bar{3}c$
Volume (hex.)	365.6 $Å^3$	321.0 $Å^3$	367.8 $Å^3$
Cell Contents (hex.)	$3[BaMg(CO_3)_2]$	$3[CaMg(CO_3)_2]$	$6[CaCO_3]$
Density (calc.)	3.840	2.872*	2.711
(obs.)	3.837 ± 0.005	2.86*	—

* Quoted from Zen (1956).

CHEMISTRY

Except for the determination of CO_2, the classical procedures of Hillebrand *et al.* (1953) were followed in the chemical analysis of norsethite which was made on a 0.1 gm. sample obtained from a single specimen. Carbon dioxide was determined volumetrically by measuring the gas evolved when the sample was treated with (1+3)HCl and, after reducing to standard conditions, applying the factor to convert volume of CO_2 to mass (Fahey, 1946).

The quantitative spectrographic analysis for minor elements in norsethite, cited below, was made by Harry Bastron of the U. S. Geological Survey:

Ca	0.40	Sn	0.002
Na	0.2	Ti	0.001
Fe	0.15	Cu	0.0005
Mn	0.049	Cr	0.0004
Sr	0.022	Be	0.0002
Al	0.016		

Looked for, not found: Ag, Au, Hg, Ru, Rh, Pd, Ir, Pt, Mo, W, Re, Ge, Pb, As, Sb, Bi, Te, Zn, Cd, Tl, In, Co, Ni, V, Ga, Sc, Y, Yb, La, Zr, Th, Nb, Ta, U, Li, P, and B.

The chemical analysis of norsethite is given in Table 3. The formula derived from this analysis is $BaMg(CO_3)_2$. The recalculated chemical analysis is in good agreement with the theoretical composition.

TABLE 3. CHEMICAL ANALYSIS OF NORSETHITE, $BaMg(CO_3)_2$
Analyst: J. J. Fahey

	Determined Per Cent	Recalculated	Molecular Ratios	Theoretical Composition
BaO	52.9	53.5	1.00	54.44
CaO	0.5	0.5		
MgO	13.9	14.0	1.00	14.31
FeO[a]	0.4	0.4		
MnO	0.1	0.1		
CO_2	31.2	31.5	2.01	31.25
Na_2O[b]	0.2			
SiO_2[c]	0.3			
Insol.[d]	0.4			
Total	99.9	100.0		100.00

[a] Total iron as FeO.

[b] Determined spectrographically by Harry Bastron.

[c] Soluble in (1+3)HCl.

[d] Insoluble in (1+3)HCl.

Using the measured specific gravity determination of 3.837, the chemical analysis in Table 3, and the cell constants for norsethite, the experimental molecular weight of the unit cell is 844.6. The calculated cell contents approach very closely the formula $3[BaMg(CO_3)_2]$.

ACKNOWLEDGMENTS

We are grateful to these colleagues in the U. S. Geological Survey for their assistance: Howard T. Evans, Jr., who contributed helpful advice and discussion; Daniel E. Appleman, who calculated the *d*-spacings on a digital computer; Harry Bastron, who made the spectrographic analysis; and Isidore Adler, who checked the crystals of norsethite for piezoelectricity.

REFERENCES

DONNAY, J. D. H. AND NOWACKI, WERNER (1954), Crystal Data. *Geol. Soc. America Memoir* **60**.

FAHEY, J. J. (1946), A volumetric method for the determination of carbon dioxide *in* Wells, R. C. and others, Contributions to geochemistry, 1942–45; *U. S. Geol. Survey Bull.* **950,** 139–141.

HILLEBRAND, W. F., LUNDELL, G. E. F., BRIGHT, H. A., AND HOFFMAN, J. I. (1953), Applied inorganic analysis, 2nd ed. John Wiley and Sons, Inc., New York.

HOWIE, R. A. AND BROADHURST, F. M. (1958), *X*-ray data for dolomite and ankerite: *Am. Mineral.*, **43,** 1210–1213.

INTERNATIONALE TABELLEN ZUR BESTIMMUNG VON KRISTALLSTRUKTUREN (1935), *I*, p. 264. Gebrüder Borntraeger, Berlin.

SWANSON, H. E. AND FUYAT, RUTH K. (1953), Standard *X*-ray diffraction powder patterns: *U. S. Natl. Bur. Standards Circ. 539*, **2,** 51–54.

ZEN, E-AN (1956), Correlation of chemical composition and physical properties of dolomite: *Am. Jour. Sci.* **254,** 51–60.

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NOTES AND NEWS

AN OCCURRENCE OF SAPONITE NEAR SILVER BAY, MINNESOTA

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H. Lepp, *Dept. of Geology, University of Minnesota, Duluth Branch.*

Introduction

Saponite and saponite-like minerals (thalite) were described from the flows of the north shore of Lake Superior by some of the first geologists in the area (Winchell, 1900). These minerals subsequently escaped attention until 1954 when a high concentration of a white clay mineral was discovered in altered basaltic flows during the construction of the Reserve Mining Company's taconite plant at Silver Bay, Minnesota. This clay mineral was first definitely identified as saponite by Whelan at the University of Minnesota, utilizing *x*-ray diffraction.

Following the discovery of the saponite near Silver Bay, field work by Lepp showed that saponite is acutally a common minor constituent of the Keewanawan flows of the north shore of Lake Superior. The saponite occurs in amygdules and in fracture zones in these volcanics. It varies in color from white to tan to light green and is usually associated with one or more of the zeolites, and with calcite and quartz. Its occurrence as a lining or rim in certain amygdules suggests that it may be an alteration product of one or more of the zeolites.

The laboratory work described in this paper was done by Whelan at the University of Utah. The mineralogic and chemical analyses reported herein were all conducted on saponite from the Silver Bay locality, because this was the best source of pure material.

Optical and Physical Properties

The saponite is white but is sometimes stained to a very light tan. It has a soapy feel and a hardness of two. Its specific gravity, as determined with a Berman microbalance, is 2.10+0.02. While crushing saponite fragments for laboratory studies, several were found to contain round, frosted, quartz fragments up to 1 mm. in diameter. These were removed by hand-picking. The crushed and ground saponite contained less than two per cent impurities, chiefly on unidentified tabular mineral, barely visible under high magnifications. The saponite is anisotropic with a mean index of refraction of about 1.49 and moderate birefringence. It exhibits a radial fibrous to matted fibrous habit under the petrographic microscope and an irregular habit under the electron microscope.

X-RAY DIFFRACTION DATA

The saponite was first identified from a powder photograph taken at the University of Minnesota. Later work was done at the University of Utah with a Norelco high-angle diffractometer utilizing CuK_α radiation. A depression mount was used to hold the sample. The data from the Minnesota saponite, together with a pattern of saponite from Cathkin near Glasgow, Scotland (Faust and Murata, 1953) are given in Table 1. Treatment of an oriented smear with ethylene glycol expanded the basal (001) refraction of the Minnesota saponite to 18.0 Å.

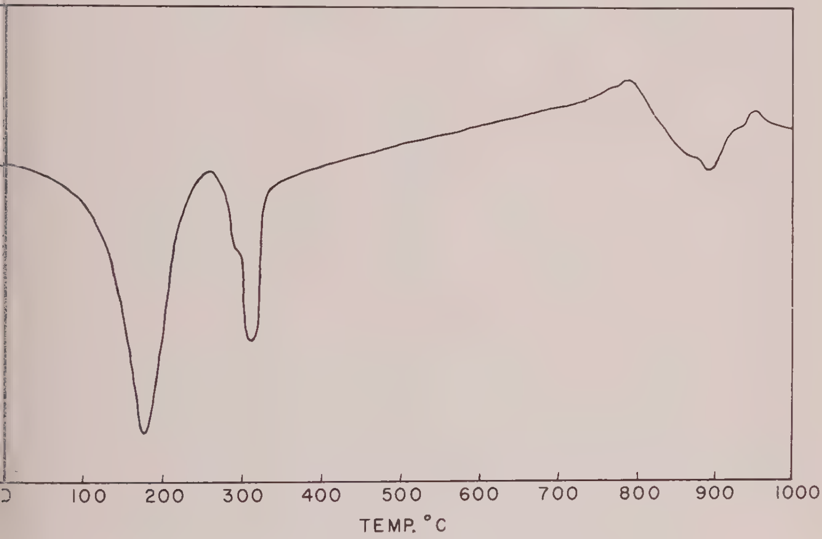

FIG. 1. DTA curve, Silver Bay saponite.

This saponite would have an approximate structural formula of $Mg_{3.0}Al_{0.6}Si_{3.4}O_{10}(OH)_2 \cdot nH_2O$, $X=0.6$. The analyses indicate that calcium is the exchangeable interlayer ion.

DIFFERENTIAL THERMAL ANALYSIS

The DTA curve of this saponite is shown as Fig. 1. The first endohermic reaction (175° C.) represents the loss of interlayer water. The econd endothermic reaction (310° C.) probably represents the loss of water coordinated around interlayer ions. This reaction occurs at a igher temperature than is usual for montmorillonite-type minerals. Usually the loss of coordinated water is represented by a break on the igh temperature side of the first endothermic reaction. The two low temperature endothermic reactions make the DTA curve of this saponite similar to curves of vermiculite (Grim, 1953, p. 199). Several runs were

TABLE 1. *X*-RAY POWDER DATA FOR SAPONITE DRIED AT ROOM TEMPERATURE (Cu/Ni; 1.5418 Å)

Saponite, Silver Bay, Minnesota			Saponite, Cathkin near Glasgow, Scotland (Faust and Murata, 1953)			
d(Å)	I*	Notes	*d*(Å)	I	Notes	Miller Indices
15.0	100		14.8	vs		(001)
			7.71	m	Broad	(002)
4.93	54		5.14	m	Broad	(003)
4.58	100		4.59	ms	Broad	(110)(020)
			4.34	vvf		
3.71	32		3.79	vw		(004)
3.04	88		3.09	m		(005)
2.969	90					
2.660			2.613	m		
	96	Broad Band	2.545	m	Diffuse	(200)
2.436						
2.287	28					
2.136	20					
1.875	20		1.852	vvf		
1.725	28		1.747	w		(150)
			1.703	w		(310)
1.670	12					
1.599	8					
1.530	10		1.543	s	Broad	(060)
			1.498	vvvf		
1.423	8		1.458	vvvf		
1.361	20					
1.326			1.327	m	Broad	(260)
	40					
1.311						
			1.278	vvvf	Broad	(400)
			0.999	vvvf	Diffuse	
			0.890	vvvf	Broad	(550)(390)

* Intensities of 00*l* reflections based on oriented aggregates.

CHEMICAL COMPOSITION

A spectrochemical analysis was made with the following results:

Major: Mg, Si, Al, Ca.
Minor: Fe, Mn.
Trace: Co, Ni (Determined semiquantitatively as 0.04%).
Not Found: Sb, As, Ba, Be, Bi, B, Cd, Cr, Cb, Cu, Ga, Sn, Ti, W, V, Zn, Zr.

A partial wet analysis is given in Table 2.

TABLE 2. CHEMICAL ANALYSES

	Silver Bay Saponite		Thalite, Knife River, Minn. (Winchell, 1900) (P-168)
SiO_2	42.8		42.38
Al_2O_3	6.2		7.37
MgO	25.2		23.29
CaO	4.9		5.82
Loss on ignition+120° C.	9.1		7.80
H_2O^-	11.9		10.38
Fe (total)	0.35	Fe_2O_3	2.65
		K_2O	0.19
		Na_2O	0.36
Total	100.45		99.94

Analyst: Lester Butcher.

made to determine if impurities were responsible for the 310° C. reaction. Impurities were not the cause, as this reaction was reproducible both as to temperature and size in samples over 98 per cent saponite.

INFRARED ABSORPTION SPECTRUM

The infrared absorption spectrum was determined on a Perkins Elmer Model 21 double-beam spectrometer with a NaCl prism. One mg. of saponite per 400 mg. infrared grade potassium bromide was used for disks. The spectrum is not definitive. Bands are as follows: O-H stretch, 3.0; O-H bend 6.18; and broad silicate bands at 9.7 and 10.25. This spectrum is generally comparable to those of other montmorillonite-type minerals.

SUMMARY AND CONCLUSIONS

Saponite of the composition $Mg_{3.0}Al_{0.6}Si_{3.4}O_{10}(OH)_2 \cdot nH_2O$, $X=0.6$, Ca/2, occurs in the Keweenawan basalt flows at Silver Bay and elsewhere along the north shore of Lake Superior. Its fibrous habit indicates that it may have formed by the alteration of a fibrous zeolite.

ACKNOWLEDGMENT

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REFERENCES

FAUST, G. T., AND MURATA, K. J., 1953, Stevensite redefined as a member of the Montmorillonite group: *Am. Mineral.*, **38,** 973–987.

GRIM, R. A., 1953, Clay Mineralogy: McGraw-Hill, N. Y., p. 199.

WINCHELL, N. H., 1900, Geology of Minnesota, Vol. 5, Final Report, Geological Survey of Minnesota.

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SIX-LAYER ORTHO-HEXAGONAL SERPENTINE FROM THE LABRADOR TROUGH

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Brindley and von Knorring (1954) described a new variety of ortho-antigorite from Unst in the Shetland Islands. In an *x*-ray powder pattern the mineral is characterized by a band of eleven closely spaced lines with the band head at (020). These lines indicated a superstructure parameter in either the *x* or *z* direction. By analogy with synthetic 6-layer Ge analog of serpentine prepared by Roy and Roy (1954), Zussman and Brindley (1957) re-indexed the pattern on the basis of a 6-layer ortho-hexagonal cell ($c=43.59$ Å) and demonstrated excellent agreement between calculated and observed *d*-values. The new polytype was called 6-layer ortho-hexagonal, or Unst-type, serpentine. Additional occurrences of this mineral are rare. Gillery (1959) reported 6-layer mixed with 1-layer serpentine from films supplied by W. S. Bailey, University of Wisconsin.

In 1957, during the course of an investigation of the serpentinized ultramafic sills along the eastern side of the Labrador Trough (Quebec-Labrador), the writer collected unusual serpentine material which was subsequently identified as the Unst-type.

OCCURRENCE

The occurrence is located 3.5 miles east of Thompson Lake at 55°20′ N., 66°10′ W. Thompson Lake is 45 air miles northeast of the town of Knob Lake, Quebec-Labrador. The mineral occurs in veins cutting a serpentinite sill. The vein material is naturally broken up into conchoidally fractured, potsherd-like pieces. It is dull dark green on the fresh surface and completely grainless, texturally resembling flint. It is monominerallic and free of even the usual magnetite impurity of the serpentinites. The sill is an altered wehrlite (olivine-clinopyroxene) which has been largely converted to antigorite, chrysotile and tremolite, with remnants of chrysolite and diopsidic augite. Both the sill and the surrounding country rocks (metasediments and metavolcanics) have mineralogies consistent with the epidote-amphibolite facies.

OPTICAL

In thin section, with transmitted light, the vein rock is medium green. The grain size is too small to be clearly resolved and interference figures are unobtainable. The birefringence appears to be of the order of 0.003.

It looks quite similar to the petrographically recognized "mineraloid" called serpophite (Lodochnikov, 1936; Kerr, 1959, p. 415). Crushed fragments immersed in oil showed a fair match around 1.565. Each fragment, of course, consisted of an aggregate of minute grains.

CHEMICAL

An analysis of the mineral is given in Table 1. Zussman (1956), Brindley (1954, 1956), and Brindley and von Knorring (1954) have already noted the difficulties in assigning a structural formula to the Unst-type serpentine. A variety of forms are possible depending on the assumptions used. Without going further into the matter, the structural formula below was calculated on the basis of 18 oxygens which is a standard first approximation and serves for comparison.

$[Mg_{5.277}Mn_{0.004}Fe''_{0.101}Fe'''_{0.243}Cr_{0.003}Al_{0.064}Na_{0.031}Ti_{0.005}]$ 5.734 atoms
$[Si_{3.611}Al_{0.389}]$ 4 atoms
$[O_{9.373}(OH)_{8.627}]$ 18 atoms

For purposes of computation all R_2O was calculated as Na_2O.)

This formula is similar to the 18-oxygen formulae of Brindley and von Knorring (1954) in the following respects: the silicon ion content is below, and the hydroxyl ion content above the ideal proportions by amounts larger than analytical error; the octahedral total is below the ideal value of 6. In contrast, the Thompson Lake sample is much higher in total R_2O_3 than the analyzed samples from Unst.

Gillery (1959) made a hydrothermal study of Mg-Al serpentines and chlorites. His starting gels were mixed according to: $(6-x)MgO$, xAl_2O_3, $(4-x)SiO_2$, $4H_2O$. Fibrous serpentines lie between $x=0$ and $x=0.24$ (approx.). Natural platy serpentines are stable between $x=0.24$ and $x=0.50$. Above 0.50 chlorite is stable, though 1 and 6-layer serpentines may form metastably as transient phases. On the basis of Gillery's

TABLE 1. CHEMICAL ANALYSIS OF 6-LAYER SERPENTINE, THOMPSON LAKE, QUEBEC-LABRADOR

SiO_2	38.50	Na_2O K_2O	0.17
TiO_2	0.07		
Al_2O_3	4.09	H_2O^+	13.79
Fe_2O_3	3.52	H_2O^-	0.94
FeO	1.29	CO_2	0.00
MnO	0.05	Cr_2O_3	0.05
MgO	37.75		
CaO	0.00	Total	100.22

Analyst: Dr. H. B. Wiik, Helsinki, 1960.

diagram (Fig. 1, p. 149) the Thompson Lake sample lies at $x=0.35$ R_2O_3. With respect to the 18-oxygen formula given above the partition of trivalent ions between tetrahedral and octahedral positions is 0.39 and 0.32, respectively. Gillery's formula ideally implies equality between these two positions.

It is puzzling that the analyzed Unst samples (Brindley and von Knorring, 1954) give values of x at 0.11 and 0.12 R_2O_3, which places them in the field of fibrous serpentines on Gillery's diagram. However, Gillery examined compositions at $x=0$ and $x=0.25$ and none between. He based his break between fibrous and platy forms (approx. 0.24) on the statement of Nagy and Faust (1956) that analyses in the literature show that fibrous polytypes may carry up to $2.9 \pm 1.9\%$ R_2O_3. However, the very careful analyses of Kalousek and Muttart (1957) give average Al_2O_3 at $0.23 \pm 0.12\%$ and Fe_2O_3 at $0.67 \pm 0.41\%$. These percentages indicate a maximum x-value around 0.06 R_2O_3 for their data on fibrous serpentine. Kalousek went to great pains to purify his sample from oxide impurities. The writer has often observed opaque grains in thin sections where the grains were barely resolvable specks of dust size. It is likely that contaminants were present in many of the older analyses, such as those referred to by Nagy and Faust. On this basis it is suggested that the break point between fibrous and platy polytypes might more properly lie around $x=0.10$ R_2O_3. This would place the platy Unst minerals in the appropriate field.

Powder Diffraction Data

The diffraction pattern of the Thompson Lake serpentine was made on a Norelco powder camera (114.5 mm.) using filtered FeKα radiation, and repeated on a General Electric XRD-5 diffractometer using filtered CuKα radiation. The observed data given in Table 2 were made from the film measurements. Forty-three lines were observed; however only the first thirty-five are reported in order to compare them with the data of Zussman and Brindley (1957).

The spacings are closely comparable to those of Zussman and Brindley (1957) with less than 0.5% difference between their observed values and those found for the Thompson Lake sample. However, the spacings (006), (025), (00,12), (02,13) and (00,18) show differences of 0.82%, 2.00%, 0.93%, 2.24% and 0.50% respectively. All these differences, except (02,13), are in the direction of being shorter than the observed spacings in the Unst sample. Although no consistent pattern is followed throughout the data, they do suggest that (00l) spacings, at least, reflect the differences in composition between the two samples. Gillery (1959) noted that the basal spacing in 6-layer serpentine decreases with

TABLE 2. X-RAY POWDER DATA

Unst (Zussman & Brindley, 1957)			Thompson Lake (FeKα, $\lambda = 1.93728$ Å)		(hkl)
$d_{\text{obs.}}$	d_{calc}	I/I_0	$d_{\text{obs.}}$	I/I_0	
7.33	7.265	100	7.27	100	006
4.597	4.610	60	4.581	50	020
4.403	4.393	10	4.420	10	023
4.250	4.245	10	4.271	10	024
4.088	4.075	10	4.006	10	025
3.903	3.892	1	3.892	1	026
3.662	3.632	100	3.628	70	00, 12
3.528	3.519	1	3.517	1	028
3.348	3.338	1	3.339	1	029
3.172	3.167	1	3.167	1	02, 10
3.015	3.005	1	3.019	1	02, 11
2.865	2.853	1	2.851	1	02, 12
2.720	2.711	1	2.781	1	02, 13
2.623	2.618	30	2.624	30	203
2.502	2.499	100	2.503	80	206
2.450	2.458	10	2.449	1	02, 15
2.425	2.422	10	2.413	5	00, 18
2.335	2.332	70	2.334	40	209
2.149	2.147	60	2.147	30	20, 12
1.9629	1.9626	70	1.9597	40	20, 15
1.8154	1.8162	1	1.8090	1	00, 24
1.7905	1.7911	10	1.7845	10	20, 18
1.7392	1.7424	10	1.7400	10	310
1.6360	1.6368	40	1.6331	20	20, 21
1.5354	1.5367	80	1.5399	60	060
1.5013	1.5033	70	1.5048	30	20, 24
1.4520	1.4530	$\frac{1}{2}$	1.4480	1	00, 30
1.4148	1.4152	20	1.4154	10	06, 12
1.3793	1.3803	20	1.3750	10	20, 27
1.3271	1.3252	10	1.3290	5	403
1.3092	1.3090	50	1.3119	20	406
1.2958	1.2975	$\frac{1}{2}$	1.2975	$\frac{1}{2}$	06, 18
1.2832	1.2832	1	1.2846	1	409
1.2759	1.2752	1	1.2720	1	20, 30
1.2100	1.2108	10	1.2105	5	00, 36

increase in x-value and increase in pressure. He explained the dependence of basal spacing on Al (or Fe‴) substitution on the basis of the higher electrostatic charge of opposite sign created by equivalent substitution in the 6 and 4 coordination layers.

Gillery makes a distinction between two types of 6-layer structure:

6(3) type with $l=2n$ usually more intense than $l=2n+1$; 6(2) type with $l=3n$ usually more intense than $l=3n+1$. Examination of the observed intensities for the Thompson Lake sample fixes it as a 6(2) type, which is also true of the Unst sample.

Although the relative intensities fit this scheme, the Thompson Lake sample gives an overall lower intensity pattern than the Unst sample, when (006) is set at 100. This difference may be more apparent than real, and can represent differences in sample handling, equipment and degree of preferred orientation in the powder.

CONCLUSIONS

The formation of 6-layer serpentine is apparently not a function of trivalent substitution alone. However, compositional data are somewhat scanty at present. It is suggested that the division between fibrous and platy serpentines may lie around 0.6% R_2O_3 (in the analysis) rather than around 4.5% as suggested by Gillery (1959). The "mineraloid," serpophite may be 6-layer serpentine, at least in part.

The writer wishes to acknowledge the assistance and comments he received from Dr. J. R. Goldsmith, Mr. D. Northrup, Dr. G. W. Brindley, and Dr. H. B. Wiik.

REFERENCES

BRINDLEY, G. W. (1954), *Am. Mineral.*, **39,** 391–393.
BRINDLEY, G. W. (1956), *Am. Mineral.*, **41,** 151–152.
BRINDLEY, G. W., AND VON KNORRING, O. (1954), *Am. Mineral.*, **39,** 794–804.
GILLERY, F. H. (1959), *Am. Mineral.*, **44,** 143–152.
KALOUSEK, G. L., AND MUTTART, L. E. (1957), *Am. Mineral.*, **42,** 1–22.
KERR, P. F. (1959), Optical Mineralogy, 3rd Ed., McGraw-Hill, N. Y.
LODOCHNIKOV, W. E. (1936), *Trans. Cent. Geol. and Prosp. Inst. U.S.S.R.*, **38.**
NAGY, B., AND FAUST, G. R. (1956), *Am. Mineral.*, **41,** 817–838.
ROY, D. M., AND ROY, R. (1954), *Am. Mineral.*, **39,** 957–975.
ZUSSMAN, J. (1956), *Am. Mineral.*, **41,** 148–151.
ZUSSMAN, J., AND BRINDLEY, G. W. (1957), *Am. Mineral.*, **42,** 666–670.

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THE GROWTH AND PROPERTIES OF COLORED QUARTZ

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Hydrothermal crystal growth refers to the use of aqueous solvents at high temperatures and high pressures to affect the solution and recrystallization of a material which is relatively insoluble at ordinary conditions. The use of this technique as a means of obtaining large crystals f relatively pure materials is perhaps best demonstrated by its successul application in the laboratory and commercial production of quartz. Walker and Buehler, 1950, Hale, 1950, Laudise and Sullivan, 1959, awyer, 1959). The fact that one can grow colorless quartz of high purity n steel vessels in a system normally considered quite corrosive is rather urprising. Most procedures for the synthesis of quartz employ a sodium ydroxide or a sodium carbonate solution as the solvent. Fortunately, nder the conditions of growth the attack of the alkali on the steel essel results in the formation of acmite (Walker and Ballman, 1954), an soluble sodium iron silicate, which coats the interior of the vessel and mits further corrosion. The formation of acmite and the protection its ating affords is perhaps the principal reason why electronic grade uartz can be grown on a laboratory or production basis without resortng to the use of inner liners of noble metals.

Considering the number of elements present in the composition of most teels, and the fact that the formation of acmite explains why only iron oes not contaminate the grown quartz, it seems clear that other ions lthough present in solution do not necessarily enter the quartz structure. In view of this and the interest in the effect of impurities on the lectrical properties of quartz a program was undertaken to purposely ntroduce ions in the quartz structure. The effect of such ions on visible olor might also offer a possible explanation of the mechanism of coloraon as seen in some naturally occurring quartz species such as citrine r rose quartz.

EXPERIMENTAL

The crystals obtained in this study were grown in high pressure steel utoclaves using a modified Bridgman seal or welded closures. Both these esigns have been previously described (Walker, 1954, Laudise and ullivan, 1959). Nutrient quartz was placed in the bottom of the vessel nd a frame holding the seed crystals whose principal surface was

(0001) was placed in the upper region. A perforated metal disc was placed between the two regions and acted as a baffle to separate the dissolving and the crystallizing zones. The action of the baffle promotes the growth of crystals of uniform dimensions throughout the entire growing region.

The autoclaves were then filled to the desired fraction of the free volume with the solvent, closed, and placed in furnaces in which the desired temperature and temperature differential were maintained with a Leeds-Northrup Micromax controller. Temperature readings were made using chromel-alumel thermocouples strapped to the exterior of the vessels and recorded daily for the duration of each experiment which lasted about 15 days.

All experiments were carried out in 1.0 molar potassium carbonate solutions at an average temperature of 370° C. and a degree of filling of the autoclave of 80 or 85% corresponding to a pressure of about 25,000 psi (Kennedy, 1950). The doping agent was put in the nutrient zone either as the metal or as the oxide. A similar technique for quartz doping has been used by other investigators (Stanley and Theokritoff, 1956, Augustine, 1957).

At the termination of a run the crystals were removed from the autoclave and their dimensions measured for growth rate calculations. The crystals were then sectioned for spectrochemical analysis, optical absorption studies and electrical measurements.

RESULTS AND DISCUSSION

Previous quartz doping studies by the author (Walker and Ballman, 1954), and others (Thomas and Brown, 1952,* Tsinober, *et al.*, 1959) had shown a slight green coloration in quartz grown from potassium hydroxide solutions and in view of this it was decided to further study the use of potassium compounds as solvents. The first such run using potassium carbonate as the solvent in a steel autoclave produced a dark green quartz almost black in appearance. Spectrochemical analyses of this material showed iron, 0.05 wt. %, manganese, 0.01 wt. %, and beryllium 0.008 wt. %. Both manganese and beryllium are minor constituents of the steel composition. Figure 1 shows the crystals produced in this run compared to a colorless crystal grown in a steel autoclave in sodium hydroxide solution. The crystals were well formed but showed a few areas with small fractures which appear to be the result of the inclusion of the foreign ion since crystals grown under similar conditions without the additives are quite free of this imperfection. The next run was made in an inert system (all silver) in which the iron could be added in controlled amounts and thus offer a means of doping with particular levels of the desired impurity. The results of this run however were rather surprising in that perfectly colorless quartz was produced containing little or no iron (.001%), even though iron was available in solution at a 1% by weight concentration. It appeared then that in order to include iron in quartz a carrier ion was needed for charge balance. Beryllium was chosen over manganese since its relatively small ionic radius should permit it to be included in the quartz structure with the least difficulty. A new run was carried out again using metallic iron (1% by wt.) but this time with the addition of beryllium (0.002% by wt.) as the carrier ion and like the first run it produced a green colored quartz. The color produced however was of lower intensity than the first run and of a slightly different hue. Figure 2 shows a crystal produced in this run.

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* In a recent publication a green and brown colored synthetic quartz was produced in steel autoclaves with a potassium carbonate solvent. Results similar to ours were obtained regarding colors produced, color zoning and optical absorption.

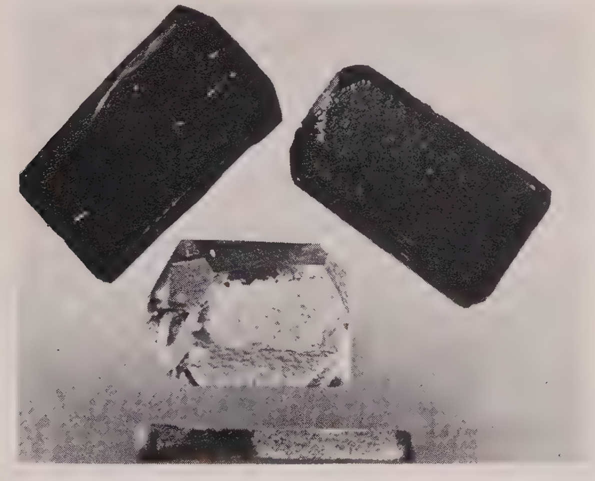

FIG. 1—Iron, manganese and beryllium doped synthetic quartz *vs.* colorless synthetic.

The color in both sets of crystals is not homogeneous but is composed of light and dark bands of green separated by zones of yellow and diminishes as the growth progresses. It was apparent from the diminishing color that the phenomenon responsible for the production of color ceased to occur after the early stages of growth. Figures 3 and 4 show the banded nature of the colored material.

Since the color produced in the grown material is composed of both green and yellow bands, both ferrous and ferric ions are presumably

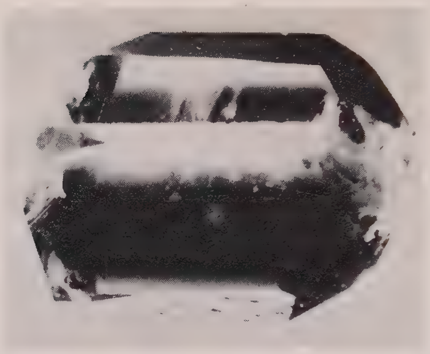

FIG. 2—Iron and beryllium doped synthetic quartz.

present in the crystal. This is not particularly surprising since recent work at the Bell Telephone Laboratories (Laudise, Crocket and Ballman, 1959) has shown magnetite to be the phase that forms under the reducing conditions in this hydrothermal system. A plausible mechanism then for the coloring effect is that of metallic iron going to ferrous and ferric ions in solution and then forming the stable magnetite phase.

Equation 1 shows this over-all reaction and equations 2, 3, and 4 show a possible stepwise formation of ferrous and ferric ions leading to the production of magnetite.

$$3Fe^\circ + 4H_2O \leftrightarrows Fe_3O_4 + 4H_2\uparrow \qquad \text{Eq. 1.}$$

$$Fe^\circ + 2H_2O \leftrightarrows Fe(OH)_2 + H_2\uparrow$$

$$Fe(OH)_2 \leftrightarrows Fe^{++} + 2OH^- \qquad \text{Eq. 2.}$$

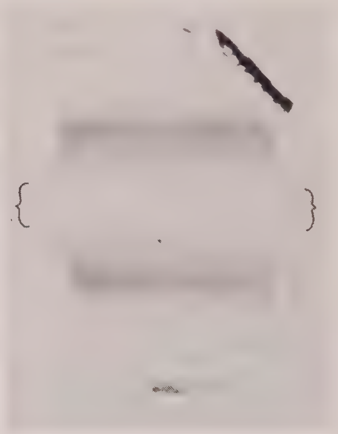

FIG. 3 (left)—Cross section cut parallel to *c* axis of iron, manganese and beryllium doped sample showing seed area marked by brackets and zonal distribution of color.

FIG. 4 (right)—Cross section cut parallel to *c* axis of iron and beryllium doped sample showing seed area and zonal distribution of color.

$$Fe(OH)_2 + 2H_2O \leftrightarrows Fe(OH_3) + H_2\uparrow$$

$$Fe(OH)_3 \leftrightarrows Fe^{+++} + 3OH^- \qquad \text{Eq. 3.}$$

$$Fe(OH)_2 + 2Fe(OH)_3 \rightleftarrows Fe_3O_4 + 4H_2O \qquad \text{Eq. 4.}$$

oloration takes place only while there is a high concentration of rrous and ferric ions in solution as the metallic iron is being oxidized. nce the metallic iron surface is all converted to magnetite the concen- ation of ferrous and ferric ions now in solution in equilibrium with the able magnetite phase is too low for iron to be included in the crystal any quantity and color ceases to be produced.

A run was made to test this hypothesis and powdered crystalline agnetite (1% by wt.) was used as the source of iron along with beryl- um ions (BeO, 0.02% by wt.) as the carrier. This run produced per- ectly colorless quartz and appears to bear out the proposed mechanism.

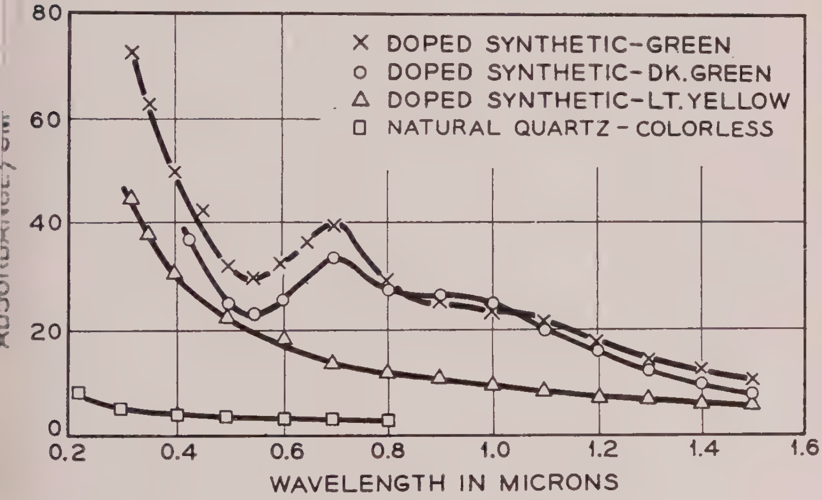

FIG. 5—Absorbance/cm. vs wavelength for synthetic and natural quartz samples.

Table 1 shows that impurity levels found in the colored samples as ell as in naturally occurring quartz. The doped samples are in general order of magnitude greater in impurity concentration.

Figure 6 shows a plot of the optical absorbance/cm. at 0.7 micron ersus wavelength for the colored samples and a representative natural uartz sample. As can be seen there are two areas of high absorption e peak occurring about 0.7 micron and another in the ultraviolet gion of the spectrum. The high absorption in the ultraviolet region is aracteristic of ferric ions in quartz as well as in other materials. Less known about where ferrous ions in quartz would show an absorption

TABLE 1. IMPURITY CONCENTRATION (WEIGHT PER CENT) FOUND IN NATURAL AND SYNTHETIC QUARTZ SAMPLES

Impurity	Natural Quartz			Doped Synthetic	
	(Colorless)	Rose (Pink)	Citrine (Yellow)	Green (Zone)	Yellow (Zone)
Fe	<0.001	—	0.001^+	0.026	0.015
Ti	—	0.005	—	—	—
Mn	—	—	—	0.016	0.005
Be	—	0.001	—	0.03	0.008

peak. However, ferrous ion generally shows an absorption peak at about 0.9–1.0 micron (Holmes and McClure, 1957) and since the conditions of the experiment indicate both ferrous and ferric ions to be present the consistent peak at 0.7 micron is most likely due to the ferrous ions.

Figure 7 shows the optical absorbance/cm versus the impurity concentration for areas of different color intensity within the same crystal. It is clearly indicated that the absorption at 0.7 micron is proportional to both the Be and the Mn concentration but not to the total iron concentration, thus it is apparently only the ferrous portion of the total iron concentration which is causing this peak.

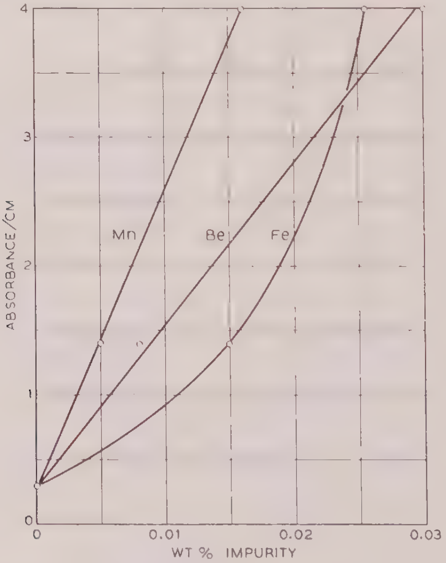

FIG. 6 Absorbance/cm. vs. impurity concentration for doped synthetic quartz.

It appears that when ferrous iron is included in the quartz it not only arries along a beryllium or manganese ion as a charge balancer but eems to permit an additional number of these ions proportional to the errous iron included to enter at the same time. This would explain why anganese and beryllium appear to obey the Beer Lambert law as hown in the plot.

It is difficult to explain why such a high concentration of beryllium s found in iron doped quartz when runs doped with beryllium alone do ot include beryllium in amounts greater than about 10 ppm.

CONCLUSIONS

The formation of acmite, an insoluble sodium iron silicate, prevents he inclusion of iron in quartz crystals grown from sodium hydroxide r carbonate solutions. Potassium carbonate solutions do not form an nalogous compound and can be used when quartz is to be iron doped. n other alkali carbonate or hydroxide solutions quartz is either not the table phase under experimental conditions or growth rates are too low o be of use.

In order for ferrous or ferric ions to be included in the quartz structure carrier ion* must be used for charge balance. Manganese and beryllium ork well with beryllium preferred due to its smaller ionic size which ermits its inclusion with the least strain.

The inclusion of iron in quartz appears to be due to a high concentraion of ferrous and ferric ions put in solution as metallic iron is oxidized y the alkaline solution and forms the stable magnetite phase.

The high optical absorption of the colored material in the ultraviolet egion of the spectrum is characteristic of ferric ion compounds, and the eak at about 0.7 micron is most likely due to ferrous ion.

The presence of both green and yellow bands in the grown quartz urther indicates the presence of both ferrous and ferric ions within the ame crystal, the green and yellow being characteristic of ferrous and erric ions respectively.

ACKNOWLEDGMENT

Thanks are due to R. A. Laudise whose discussion and suggestions ere most helpful in carrying out the work and to D. L. Wood for disussions and interpretations of absorption data during the study.

REFERENCES

UGUSTINE, F. (1957), Improving the Quality of Synthetic Quartz: *Proc. 11th Ann. Freq. Control Sym.*, U. S. Army S.C.E.L.

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* A carrier ion is any ion other than the substituting ion which must also be included presumably interstitially) to balance charges.

BROWN, E. S., THOMAS, L. A. (1952) Response of Synthetic Quartz to *X*-ray Irradiation: *Nature*, **169,** 35

HALE, D. R. (1950), *Ceramic Age*, **56,** 22.

HOLMES, O. G., MCCLURE, D. S. (1957) Optical Spectra of Hydrated ions of the Transition Metals, *J. Chem. Phys.*, **6,** 1686–1694.

KENNEDY, G. C. (1950) Pressure, volume, temperature relations in water at elevated temperatures and pressures: *Amer. J. Sci.*, **248,** 540.

LAUDISE, R. A., CROCKET, J., BALLMAN, A. A. (1959), The hydrothermal crystallization of yttrium iron garnet and yttrium gallum garnet and a part of the crystallization diagram Y_2O_3-Fe_2O_3-H_2O-Na_2CO_3: *J. Phys. Chem.* **65,** 359, 1961.

LAUDISE, R. A., SULLIVAN, R. A. (1959), Pilot plant production of synthetic quartz: *Chem. Eng. Prog.*, **55,** 5.

SAWYER, C. B. (1959), Progress in engineering cultured quartz for use by the crystal industry: *Proc. 13th Ann. Freq. Control. Sym.*, U. S. Army S.C.E.L.

STANLEY, J. M., THEOKRITOFF, S. (1956), Incorporation of impurities in synthetic quartz crystals: *Am. Mineral.*, **41,** 527.

TSINOBER, L. I., CHENTSOVA, L. G., SHTERNBERG, A. A. (1959), The green and brown colors of synthetic quartz crystals: *Growth of Crystals*, Edited by A. V. Shubnikov and N. N. Sheftal, Vol. 2, Translated by Consultants Bureau Inc., New York, N. Y. p. 45 of translation.

WALKER, A. C. (1954), Hydrothermal Growth of Quartz Crystals: *Ind. Eng. Chem.* 1670.

WALKER, A. C., BALLMAN, A. A. (1954), Synthesis of quartz crystal: *1st Interim Report*, U. S. Army S.C.E.L. No. DA-36-039-SC-64493, Bell Telephone Laboratories.

WALKER, A. C., BUEHLER, E. (1950), Growing large quartz crystals: *Ind. Eng. Chem* **42,** 1369.

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COMMENT ON "GROWTH AND PROPERTIES OF COLORED QUARTZ"

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The interesting results of Ballman (preceding article) on the differences in concentration of various ions in the different crystallographic zones suggest the following explanations which supplement or modify the author's conclusions.

(1) Keith and Tuttle (*Am. J. Sci.*, **Bowen Volume**, 1952, p. 203) found a similar zoning of alternate "segments" of different color in natural quartz (after irradiation). It is interesting to note that such crystals as well as those grown by Ballman provide examples of the chemical inhomogeneity of a "single phase" which still qualifies as a phase in the context of the Phase Rule.

(2) Ballman suggests that a "carrier ion must be used for charge balance" in order for ferrous or ferric ion to be included in the quartz structure. Since their valence is also lower than Si^{4+}, it is obvious that the elements suggested (Be^{2+}, Mn^{2+}) cannot form half-breed derivatives

such as (for example) P^{5+} serving as a 'carrier' for Al^{3+} and together proxying for $2Si^{4+}$. It may be implied that Be^{2+} could accept interstitial sites, which is feasible, but it would be much less likely that Mn^{2+} would do so.

Energetically, what appears to be most likely is that a stuffed derivative is formed rather than adding ions in interstitial sites. Thus, $Be^{2+^{IV}}$ replaces $Si^{4+^{IV}}$ with Mn^{2+}, Fe^{2+} and Fe^{3+} being added in the stuffing site to balance the loss of charge.

Alternatively, Fe^{3+}, Be^{2+} for Si^{4+} with Mn^{2+}, Fe^{2+} (and remaining Fe^{3+} if any) in the stuffing site.

If Fe^{2+} were in lattice sites rather than Fe^{3+} it would require that twice as many total charges be realized by the stuffing ions. In fact, the analysis of Fig. 5 cannot be quantitatively explained on the basis of any of these schemes, since the atomic concentration of Be is too high to be compensated for by putting all the iron and manganese in the stuffing site. If this amount of Be^{2+} is actually incorporated, almost certainly one should detect by infra-red spectroscopy appreciable $(OH)^{-}$ proxying for O^{2-}.

The absorption due to Fe^{3+}, Fe^{2+} or Mn^{2+} in the stuffing site will, of course, not be the same as the absorption in other commoner crystal fields and hence one cannot extrapolate from the color of known compounds to the 'color' of an ion in an interstitial or stuffing site.

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THERMOLUMINESCENCE MEASUREMENTS WITH RAPID HEATING

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Recent papers in the *American Mineralogist* have described refined thermoluminescence measuring apparatus for minerals (Ashby and Kellagher, 1958; Lewis, *et al.*, 1959). The heating rate used for these is about 2° C. per second or less. Slow heating rates were first used in this laboratory (Saunders, 1953), but a fast heating instrument has been found to be more sensitive to low levels of thermoluminescence and increases the number of determinations which can be made per hour. A consequence of the fast-heat feature, however, is a decrease in temperature control and precision. Houtermans, *et al.* (1957) has also described a fast heating thermoluminescence instrument and discusses its relative advantages.

The apparatus described here normally employs a heating rate of 20 to 30° C. per second, but if required, heating rates of 90° C. per second may be attained. Although the total number of thermoluminescence photons is independent of the rate of heating, a fast heating rate releases more photons per second, thus leading to a more easily detected, intense light. The time of heating is only a few seconds and the whole

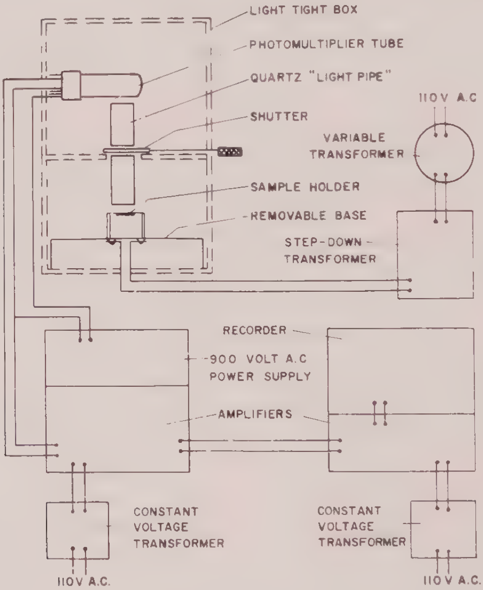

Fig. 1. Fast-heat thermoluminescence measuring device.

operation can be completed in about 5 minutes per sample, including grinding, loading, heating and cooling.

The apparatus is shown in Fig. 1 (Ammentorp, 1957). The heater is a strip of nichrome ribbon $1\frac{1}{2}$ inches long, $1\frac{1}{4}$ inches wide and 0.027 inch thick, mounted with spring tension on a transite base. Above it is a vertical light pipe of quartz provided with a shutter. A photomultiplier tube (1P21) receives thermoluminescent light emitted by heated crystals and the current is amplified with a circuit designed by Professor Robert J. Parent and built by Mr. Donald M. Pryor in this laboratory (Fig. 2).

The photoelectric current is recorded on a rapid recorder, Sanborn Model 127, equipped with a built-in D.C. amplifier Model 126B. Paper speed is 25 mm. per second and the light intensity curve is traced by a heated stylus on color-changing paper. The light intensity-temperature (time) graph is the "glow curve."

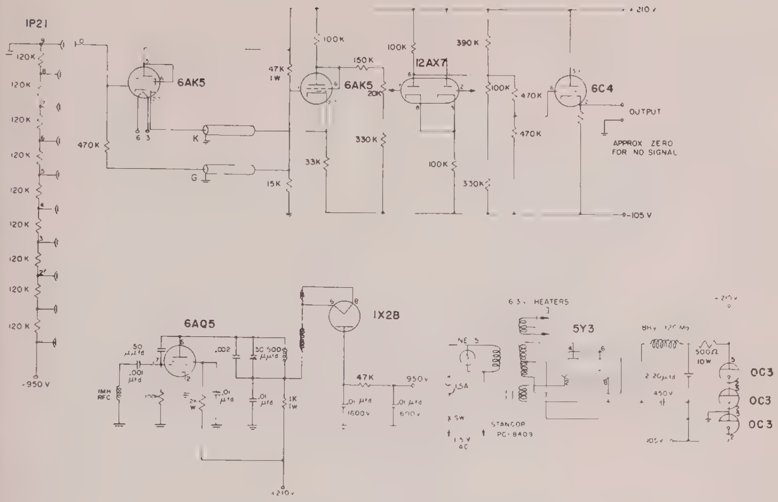

FIG. 2. Photomultiplier and amplifier.

The nichrome heater is supplied power through a 1.5 kilowatt step down transformer and the heating rate is controlled with a Variac. Temperatures from the start of heating are determined by using heat-sensitive crayons. A curve of temperature is then plotted against time for each heater power setting. The calibration curves are near linear. After red heat has been reached, power is cut off and the nichrome heating ribbon is quickly cooled by an air blast or with dry ice, ready for the next sample.

Sensitivity to thermoluminescence may also be controlled by the area and volume of sample exposed to the photomultiplier tube. A simple control technique is to pack a powered sample (100–200 Tyler) into shallow ring molds. Compaction of the powder against the sides of the ring holds the sample in place and permits transportation of the sample for weighing and loading onto the furnace. The molds make uniform sample discs with one side in intimate contact with heating elements and the other side exposed to the photomultiplier. Sample volume, geometry and heating environment may be varied according to the dimensions of the ring mold.

By adjusting sample size and/or regulating the heating rate a wide range of thermoluminescent intensities may be measured and recorded. The effect of faster heating on improving instrumental sensitivity is shown in Fig. 3.

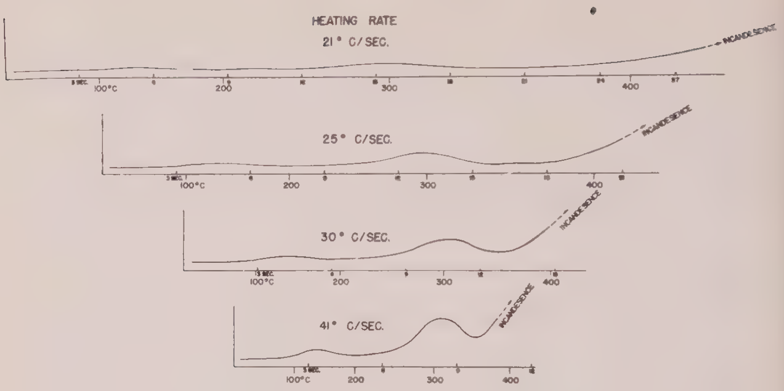

FIG. 3. Resolution of low level thermoluminescence in NaCl by fast heating.

REFERENCES

AMMENTORP, W. F. (1957), Thermoluminescence of Anhydrite: Master's thesis held by the Library, University of Wisconsin.

ASHBY, G. E. AND KELLAGHER, R. C. (1958), An apparatus for the study of thermoluminescence from minerals: *Am. Mineral.*, **43,** p. 695–706.

HOUTERMANS, E. G., JÄGER, E., SCHÖN, M., AND STAUFFER, H. (1957), Messungen der Thermolumineszenz als Mittel zur Untersuchung der thermischen und der Strahlungsgeschichte von naturlichen Mineralien und Gesteinen: *Annalen der Physik*, **20,** 283–292.

LEWIS, D. R., WHITAKER, T. N., AND CHAPMAN, C. W. (1959), Thermoluminescence of rocks and minerals. Part I. An apparatus for quantitative measurement: *Am. Mineral.*, **44,** 1121–1140.

SAUNDERS, D. F. (1953), Thermoluminescence and surface correlation of limestones: *Bull. Amer. Assoc. Petrol. Geol.*, **37,** 114–124.

THE AMERICAN MINERALOGIST, VOL. 46, MARCH-APRIL, 1961

ADSORPTION OF ETHYLENE GLYCOL AND GLYCEROL BY MONTMORILLONITE*

(Clay-Organic Studies, Part V†)

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The swelling of montmorillonite immersed in ethylene glycol or in glycerol has been used for many years to identify montmorillonite in mixtures of clay minerals. It is sometimes believed that montmorillonite has an 'affinity' for these compounds such that they are strongly absorbed from aqueous solutions. The present note describes measurements which show that they are not preferentially absorbed from aqueous solutions to any appreciable extent.

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* Contribution No. 60-32 from the College of Mineral Industries, The Pennsylvania State University, University Park, Pennsylvania.

† Part IV. See Hoffmann and Brindley (1961).

In previous work (Brindley and Rustom, 1958, and more particularly, Hoffmann and Brindley, 1960) isotherms for the adsorption of a variety of non-ionic organic compounds of Ca-montmorillonite from aqueous solutions have been determined to study the features of the organic molecule which affect the adsorption. Two factors were found to affect the adsorption equilibria in solution: chain-length and CH-activity. For molecules with small CH-activity, a minimum chain-length of about 6 carbon atoms is required for preferential adsorption and on this basis neither ethylene glycol nor glycerol would be expected to show preferential adsorption.

Experiments have been made to determine the adsorption isotherms of ethylene glycol and glycerol on Mg-montmorillonite from aqueous solutions. The Mg-saturated clay was used because it was immediately available and other studies (Brindley, Hoffmann and Bender, 1960) had shown that for several substances the exchangeable inorganic cation has no significant influence on the organic adsorption, at least for the ions Na^+, Ca^{2+}, and Mg^{2+}.

Suspensions containing 15 mg. clay per ml. and ethylene glycol or glycerol in concentrations varying from 2.5×10^{-2} to 50×10^{-2} molar were equilibrated for 20 hr. After centrifuging for 2 hr., the organic content of the supernatant liquid was determined by dichromate oxidation. For neither compound could any depletion in concentration be detected except for small variations within the accuracy of the analytical determinations (±1%). Therefore these compounds do not show any preferential adsorption from aqueous solutions on montmorillonite.

Part of the clay paste remaining in the centrifuge tubes was taken with a minimum of adherent liquid and allowed to dry on glass slides. The clay-organic films were then examined in a stream of dry air by x-ray diffraction using a Phillips Norelco diffractometer with filtered $CuK\alpha$ radiation. The results showed that complexes were formed containing one layer of water, one layer of organic material, two layers of organic material, or mixtures thereof according to the organic concentration of the adherent solution in the initial clay paste.

The spacings for the one- and two-layer organic complexes are $13.9_0\pm0.1$ Å and $16.8_5\pm0.1$ Å for ethylene glycol, $13.9_5\pm0.1$ Å and $17.7_5\pm0.1$ Å for glycerol respectively, and $11.9_5\pm0.0_5$ Å for a single water layer.

It has been pointed out already (Hoffmann and Brindley, 1960) that the type of complex formed after drying a clay-water-organic mixture does not depend so much on the adsorption equilibria existing in aqueous solution as on the relation of the volatility of the organic compound to that of water. Among the substances investigated, two extremes have been found:

(i) Substances with high volatility may be adsorbed strongly from aqueous solutions under equilibrium conditions, but may not form complexes on drying as both the water and the organic substance evaporate.

(ii) Substances with low volatility which show little or no adsorption from aqueous solution, may still form complexes on drying because the water evaporates leaving the clay and organic material behind.

The second mechanism has already been proposed by Bradley (1945) who suggested that ethylene glycol may form complexes with montmorillonite by replacement of the adsorbed water due to their difference in volatility. This is now confirmed experimentally. Ethylene glycol and glycerol belong to the second group since they show no preferential adsorption from aqueous solution under equilibrium conditions but form complexes after drying due to their low volatility compared with that of water.

Grateful acknowledgement is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of this reasearch.

REFERENCES

BRADLEY, W. F., (1945), Molecular associations between montmorillonite and some polyfunctional organic liquids. *J. Am. Chem. Soc.* **67,** 975–981.

BRINDLEY, G. W., HOFFMANN, R. W., AND BENDER, R., (1960), unpublished data.

BRINDLEY, G. W., AND RUSTOM, MAHMOUD, (1958), Adsorption and retention of an organic material by montmorillonite in the presence of water, *Am. Mineral.*, **43,** 627–640.

HOFFMANN, R. W., AND BRINDLEY, G. W., (1960), Adsorption of nonionic aliphatic molecules from aqueous solution on montmorillonite (Clay-Organic Studies, Part II). *Geochim. et Cosmochim. Acta*, **20,** 15–29.

HOFFMANN, R. W., AND BRINDLEY, G. W., (1961), Infrared extinction coefficients of ketones adsorbed on Ca-montmorillonite in relation to surface coverage (Clay-Organic Studies, Part IV). Submitted to *J. Phys. Chem.*

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LATTICE CONSTANTS OF THE CALCIUM-MAGNESIUM CARBONATES

JULIAN R. GOLDSMITH,* DONALD L. GRAF,† AND HUGH C. HEARD‡

In an earlier publication (Goldsmith and Graf, 1958) lattice constants of several dolomites and of synthetic magnesian calcites containing up to about 20 mol per cent $MgCO_3$ were presented. Since these data appeared, the system $CaCO_3$-$MgCO_3$ has been investigated at higher temperatures and CO_2 pressures, and single phase solid solutions were successfully prepared over the whole range from $CaCO_3$ to $CaMg(CO_3)_2$ (Goldsmith and Heard, 1961). The present paper is based upon measurements made on some of the latter samples. The experimental conditions under which these samples were prepared are given in Table 1.

Powder *x*-ray diffraction patterns were taken of these samples using

TABLE 1. EXPERIMENTAL CONDITIONS UNDER WHICH THE SYNTHETIC CALCIUM MAGNESIUM CARBONATES DISCUSSED IN THIS PAPER WERE PREPARED

The samples were contained in sealed Pt capsules in an internally heated gas system, escribed elsewhere (Goldsmith and Heard, 1961).

Sample Number	Mol Per Cent $MgCO_3$	Temp. (° C.)	CO_2 Pressure (Kb.)	Time (minutes)
C-213	10	945– 950	5.0	45
C-291	10	684– 686	2.0	180
C-214	20	945– 950	5.0	45
C-226	20	884– 892	4.0	90
C-217	30	978– 981	5.0	40
C-207	40	1074–1075	8.5	30
C-203	40	1140–1150	10.0	30
C-193	42.5	1144–1150	10.0	30
C-194	45	1144–1150	10.0	30
C-91	45	1093–1101	8.0	12
C-182	47.5	1146–1151	10.0	25
C-102	50	1150–1155	10.0	5
C-114	50	900– 901	5.0	60

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† Illinois State Geological Survey, Urbana.

‡ Institute of Geophysics, University of California, Los Angeles.

CoKα radiation, and a_0 and c_0 were obtained from $\cos^2\theta$ extrapolations of the appropriate back-reflections. These data are plotted in Figs. 1 and 2. The scatter of the plotted points is partly attributable to two principal factors. Small amounts of a secondary phase, presumably produced by incomplete reaction or exsolution during quenching were noted in several runs, particularly in the composition range $Ca_{70}Mg_{30}$ to $Ca_{55}Mg_{45}$. Although runs obviously imperfect in this regard were discarded, lesser inhomogeneities may exist in some of the other samples. Secondly, some of the x-ray patterns have back-reflections that, although measurable, are not as sharp as would be desired for maximum accuracy.

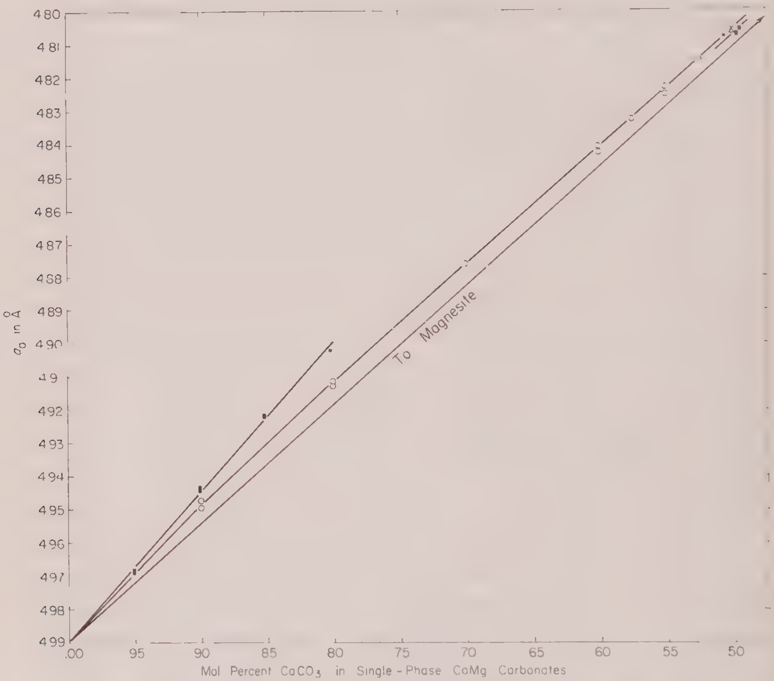

FIG. 1. The change in a_0 with composition for $CaCO_3$-rich phases in the system $CaCO_3$-$MgCO_3$. Open circles represent new measurements on disordered solid solutions; triangles, new measurements on phases with (cation-ordered) dolomite-type structures. Vertical bars are schematic representations of groups of closely similar measurements, published previously (Goldsmith and Graf, 1958).

The data of Goldsmith and Graf (1958) are also plotted in Figs. 1 and 2. There is a significant discrepancy between the two sets of data for the calcites containing up to 20 mol per cent $MgCO_3$. As a further check, Miss Juanita Witters of the Illinois Geological Survey has redetermined

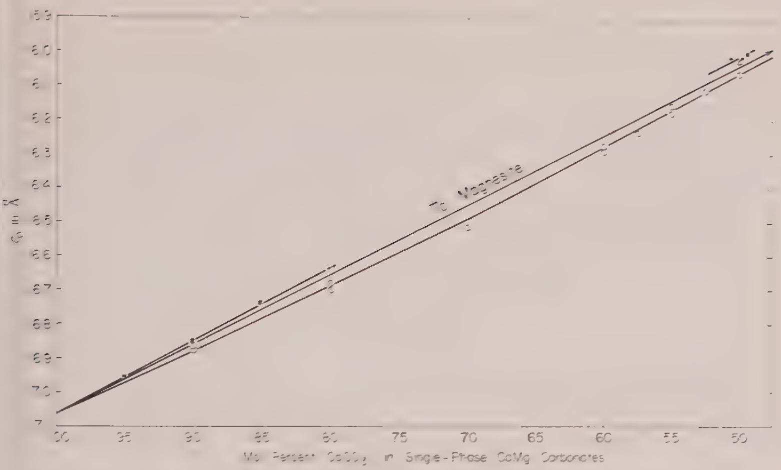

FIG. 2. The change in c_0 with composition for $CaCO_3$-rich phases in the system $CaCO_3$-$MgCO_3$. The symbols used have the same meaning as in Fig. 1.

compositions of the approximately 20 mol per cent $MgCO_3$ mixture ed by Goldsmith and Graf (1958) and of the 20 mol per cent $MgCO_3$ xture used by Goldsmith and Heard. Her results, given in Table 2, within 1.0 mol per cent of the composition (by synthesis) of the ldsmith-Heard magnesite-calcite mixture, and indicate a probable ference in composition between the mixtures of 0.4 mol per cent. A ference of three mol per cent would be required to explain the disepancy in Figs. 1 and 2. We can offer no explanation, but prefer the

TABLE 2. EMISSION SPECTROGRAPHIC ANALYSES OF THE TWO SYNTHETIC MIXTURES USED IN PREPARING $CaCO_3$ SOLID SOLUTIONS CONTAINING APPROXIMATELY 20 MOL. PER CENT $MgCO_3$

The calibration curves were adjusted for each plate, using standards run on that plate. anita Witters, analyst.

	Goldsmith and Graf (1958)		Goldsmith and Heard (This paper)	
	$MgCO_3$	$CaCO_3$	$MgCO_3$	$CaCO_3$
First Trial	17.7	82.3	18.1	81.9
Second Trial	18.0	82.0	18.0	82.0
Third Trial	18.0	82.0	18.7	81.3
Average (Wt. Per Cent)	17.9	82.1	18.3	81.7
Mol Per Cent	20.6	79.4	21.0	79.0

Table 3. Cell Constants for Some Synthetic and Natural Calcium Carbonate Solid Solutions (see also Table 1)

The cell constants used for the ordered Gabbs and Serra das Eguas dolomites in the Guinier Δa_0 and Δc_0 determinations are those published by Goldsmith and Graf (1958); for the Lee, Massachusetts, dolomite, the mean of the published values, $a_0 = 4.8079$ Å, $c_0 = 16.010$ Å, was assumed; for the synthetic mixture of equimolar amounts of $CaCO_3$ and $MgCO_3$, the a_0 and c_0 values given below for C-114 were used. The values given in this table are the most probable ones based upon $\cos^2 \theta$ extrapolations; the final figure is obviously not significant for some samples, but it is difficult to assign probable uncertainties.

Material	a_0 in Å	c_0 in Å
A. Cation disordered or largely so		
C-213, $CaCO_3$ containing 10 mol per cent $MgCO_3$	4.9494	16.876
C-291, $CaCO_3$ containing 10 mol per cent $MgCO_3$	4.9473	16.863
C-214, $CaCO_3$ containing 20 mol per cent $MgCO_3$	4.9128	16.699
C-226, $CaCO_3$ containing 20 mol per cent $MgCO_3$	4.9115	16.698
C-217, $CaCO_3$ containing 30 mol per cent $MgCO_3$	4.8760	16.514
C-207, $CaCO_3$ containing 40 mol per cent $MgCO_3$	4.8410	16.291
C-203, $CaCO_3$ containing 40 mol per cent $MgCO_3$	4.8428	16.274
C-193, $CaCO_3$ containing 42.5 mol per cent $MgCO_3$	4.8328	16.235
C-194, $CaCO_3$ containing 45 mol per cent $MgCO_3$	4.8255	16.178
C-91, $CaCO_3$ containing 45 mol per cent $MgCO_3$	4.8233	16.156
C-182, $CaCO_3$ containing 47.5 mol per cent $MgCO_3$	4.8152	16.111
C-102, $CaCO_3$ containing 50 mol per cent $MgCO_3$	4.8050	16.061
B. Cation ordered		
C-114, Dolomite containing 50 mol per cent $MgCO_3$	4.8067	16.025
C. Dolomite cell-size changes on cation disordering		
	Δa_0 in Å	Δc_0 in Å
Synthetic mixture (C-102, C-114), 900° vs. 1155° C.		
Straumanis-mount powder x-ray films	-0.0017	$+0.036$
Adjacent strips on film taken with Guinier-type camera	-0.0026	$+0.016$
Dolomite, Lee, Mass., Unheated vs. 1155° C. (Guinier)	-0.0033	$+0.037$
Dolomite, Serra das Eguas, Brazil, Unheated vs. 1152° C. (Guinier)	-0.0048	$+0.033$
Dolomite, Gabbs, Nevada, Unheated vs. 1155° C. (Guinier)	-0.0033	$+0.030$

latest set of measurements because the initial starting materials were anhydrous end members and because of the concordance between results for the magnesian calcites and synthetic and natural dolomites. The previous magnesian calcite values were available only to 20 mol per cent $MgCO_3$ and had to be extrapolated to the dolomite composition. They led to the improbable conclusion that ordered material of dolomite composition had a larger unit cell volume than its disordered counterpart.

The new data give, for the first time, direct information on the change cell size accompanying cation disorder in dolomite, which is sum- arized in Table 3 together with cell constants for the synthetic dis- dered solid solutions and for several natural dolomites. Disordering dolomite results in a very slight decrease in a_0 and a somewhat greater crease in c_0. Considering all of the data of Table 3, $\Delta a_0 = -0.003$ Å, $_0 = +0.03_5$ Å, and $\Delta V = +0.3$ Å^3 or $+0.09\%$ of the dolomite cell lume. A material of dolomite composition with complete cation dis- der has not thus far been obtained; the materials here described are bstantially but not completely disordered (Goldsmith and Heard, 61). The comparable values for fully disordered cadmium magnesium rbonate, $CdMg(CO_3)_2$ (Goldsmith, 1958, and in preparation) are $_0 = -0.0024$ Å, $\Delta c_0 = +0.037$ Å, and $\Delta V = +0.42$ Å^3 or $+0.14\%$ of the $Mg(CO_3)_2$ cell volume.

Goldsmith and Heard (1961) show that the maximum amount of cess $CaCO_3$ that can be contained in the (ordered) dolomite structure high temperatures is approximately 7 mol per cent. Thus the compo- ion versus cell edge curves shown for ordered materials in the dolo- ite region in Figs. 1 and 2 must merge with the curves for disordered terials at the approximate molar composition $Ca_{57}Mg_{43}$, and the zone tween such curves corresponds to a region of intermediate cation der. The measurable effect is, of course, quite small, and the available ta do not justify drafting the bifurcation in Figs. 1 and 2.

ACKNOWLEDGMENTS

This investigation was supported in part by a grant-in-aid from the lifornia Research Corporation and by ONR Contract 233 (28) to ofessor G. C. Kennedy of the Institute of Geophysics.

REFERENCES

DLDSMITH, J. R. (1958), Cadmium-dolomite and the system $CdCO_3$-$MgCO_3$ (Abst.), *Geol. Soc. Amer. Bull.*, **69,** 1570–1571.

DLDSMITH, J. R. AND HEARD, H. C. (1961), Subsolidus phase relations in the system $CaCO_3$-$MgCO_3$, *Jour. Geology*, **69,** 45–74.

DLDSMITH, J. R. AND GRAF, D. L. (1958), Relation between lattice constants and com- position of the Ca-Mg carbonates, *Am. Mineral.*, **43,** 84–101.

Dr. Esper S. Larsen, Jr. died in Washington, D. C., on March 8, 1961, at the age of 82. . Larsen was a member of the faculty at Harvard for many years. He was President of Mineralogical Society of America in 1928, and received the Roebling Medal in 1941. A morial will appear in a later issue.

BORNITE FROM CHESHIRE

Dr. R. A. Howie of the University, Manchester, England, writes the following comments.

In the "Second find of euhedral bornite crystals on barite."

Living as I do in Cheshire, England, I was interested in the article "Second find of euhedral bornite crystals on barite" (*Am. Mineral.* **45**, 1062, 1960), which states that such an association had been previously reported from the "Cheshire locality in England." Barite is in fact known from Alderley Edge, where there is considerable copper mineralization, but there is no record of bornite in association with barite. However, Dana—System of Mineralogy, 6th edition, page 78, states that "bornite occurs at the copper mine in Bristol, Conn., abundant, and often in fine crystals. At Cheshire sparingly in cubes, with barite, malachite and chalcocite." It therefore seems evident that the Cheshire locality which Kullerud, Donnay and Donnay refer to is Cheshire, Connecticut.

GELATIN MOUNTS FOR MINERAL GRAINS

In the Sept.-Oct. 1960 issue of the *American Mineralogist*, Olcott described a method for mounting mineral grains which was a modification of the procedure of Marshall and Jeffries (*Soil Sci. Soc. Amer. Proc.*, **10**, 397–405). Dr. Jeffries writes that carbonates are decomposed by the formalin in the original solution B, and very satisfactory results are obtained when the formalin is omitted.

1960 PEACOCK MEMORIAL PRIZE

The Walker Mineralogical Club announces that it has awarded its Peacock Memorial Prize (1960) of two hundred dollars "for the best scientific paper on pure or applied mineralogy, including crystallography, mineralogy, petrology, ore genesis, and geochemistry," submitted by a graduate student, to Dr. Joseph E. Patchett.

Dr. Patchett's paper was entitled, "A Study of the Radioactive Minerals of the Uraniferous Conglomerate, Blind River Area." He did his work under Professor E. W. Nuffield and Professor W. W. Moorhouse at the University of Toronto (Toronto, Ontario, Canada). Dr. Patchett, a native of Middletown, New York, received his B.S. from Rutgers University, New Brunswick, New Jersey in 1952. He received his M.A. in 1954 from the University of Toronto and, following two years of service in the U. S. Army, he returned to Toronto to resume his studies. He received his Ph.D. in 1960. He is presently employed as a crystallographer with the Research Department of the Norton Company, Chippawa, Ontario.

The Walker Mineralogical Club announces also at this time that it is offering the Peacock Memorial Prize again in 1961. A copy of the announcement follows.

1961 PEACOCK MEMORIAL PRIZE

TWO HUNDRED DOLLARS—$200.00

For the best scientific paper on pure or applied mineralogy, including crystallography, mineralogy, petrology, ore genesis and geochemistry.

Conditions

1. The author of the paper shall be any graduate student enrolled in a Canadian university, a Canadian graduate student enrolled in any university, or any graduate student on a Canadian subject.
2. The paper, written in French or English, will be accepted for competition up to two years after completion of the work, even though the author may be enrolled no longer as a graduate student.

3. The paper may be in the form of:
   (a) a thesis,
   (b) a paper ready for publication,
   (c) a printed publication.

4. The paper may offer new or refined observations; or a significant synthesis and inerpretation of existing data; or some new or improved application of mineralogy to useful nds; or the results of other work of sufficient interest and value.

5. Each paper must be accompanied by a letter from the candidate's supervisor stating he nature and extent of the assistance he may have given to the work submitted.

6. The paper is to be addressed to—The Secretary, Walker Mineralogical Club, 00 Queen's Park, Toronto 5, Ontario.

7. CLOSING DATE OF THIS COMPETITION—December 31, 1961.

If no paper of sufficient merit is received, the prize will not be given. All papers submitted will be returned to their authors as soon as the judging is completed. Announcement f the award will be made in the appropriate publications.

BACK ISSUES OF *Contributions to Canadian Mineralogy*

The Walker Mineralogical Club now has complete sets of the University of Toronto tudies, Geological Series, "*Contributions to Canadian Mineralogy*" (26 issues with indexes) on microfilm, at less than one-third the cost of a set in book form.

AMERICAN CRYSTALLOGRAPHIC ASSOCIATION

The 1961 summer meeting of A.C.A. will be held at the University of Colorado, Boulder, Colorado, July 31–August 4. The local chairman is Dr. Walter M. MacIntyre, Chemistry Department, University of Colorado; and the program chairman is Dr. G. B. Carpenter, Department of Chemistry, Brown University, Providence 12, Rhode Island.

10TH ANNUAL CONFERENCE ON APPLICATIONS OF *X*-RAY ANALYSIS

This conference will be held immediately following the A. C. A. Conference, in Boulder, Colorado, on 7, 8 and 9 of August, 1961. (Note that this is Mon.-Tues.-Wed.) The sessions will be held in the new conference room of the Park Lane Hotel, Denver.

For additional information, write W. W. Mueller, Head, Metallurgy Division, Denver Research Institute, University of Denver, Denver 10, Colorado.

Erratum

In the January-February, 1961 issue of the *American Mineralogist*, the book review n page 238 of "ULTRAVIOLET GUIDE TO MINERALS" was credited to the wrong author. The author is Mr. Sterling Gleason.

BOOK REVIEWS

X-RAY ABSORPTION AND EMISSION IN ANALYTICAL CHEMISTRY. (Spectrochemical Analysis with *X*-rays), by H. S. LIEBHAFSKY, H. G. PFEIFFER, E. H. WINSLOE, AND P. D. ZEMANY, 357 pages, John Wiley and Sons, Inc., New York, 1960, $13.50.

X-ray spectroscopy as a tool for analytical purposes has advanced rapidly in recent years. What has been sorely needed to keep pace with this advance has been a good text to survey the field and function as a reference source. This book fills these needs in an admirable fashion and has already received wide scale approval by workers in the field. The authors describe lucidly the history and basic theory, the reliability of the *x*-ray methods, a variety of applications, and all the required equipment, instrumentation, and techniques.

The first part of the book is devoted to the origin and properties of *x*-rays, the measurement of *x*-ray intensity, detectors, and to the important analytical method using *x*-ray absorption. The latter part of the book is concerned with the methods based on *x*-ray emission. An important chapter on reliability of *x*-ray emission spectrography is included.

The six appendices consist of tables very useful to the practicing *x*-ray spectrochemist and a bibliography of element determinations.

Of particular interest to the mineralogist is Chapter 7 which is devoted in part to the analysis of minerals. The potential of the technique as well as some specific applications are described.

This reviewer feels that this book has great value in any laboratory performing *x*-ray spectrochemical analyses.

ISIDORE ADLER
U. S. Geological Survey
Washington, D. C.

METHODS IN GEOCHEMISTRY. Edited by A. A. SMALES AND L. R. WAGER. Interscience Publishers, New York, 1960. 464 pages. $13.50.

In this modern day, the geochemist has at his disposal an ever-increasing armament of powerful, but complex, instruments and methods for studying earth materials. The literature dealing with these new tools is mostly periodical, is widely scattered, and is, in some cases, written for audiences other than those interested in earth-sciences. For these reasons this work of Smales and Wager is a very timely one, and a very welcome one.

The book contains ten chapters (plus introduction), written by eleven experts, on methods of geochemical analysis (*sensu vasto*). These are: Collection and Preparation of Materials for Analysis; Analysis by Gravimetric and Volumetric Methods, Flame Photometry, Colorimetry and Related Techniques; Spectrochemical Analysis; Fluorescent *X* Ray Spectrography; Stable Isotope Geochemistry and Mass Spectrometric Analysis; Mass Spectrometric Isotope Dilution Analysis; Radiochemical Methods; Radioactivation Analysis; Polarography; Some Modern Chemical Separation Methods.

The list of methods covered by the book is not an exhaustive one: no mention is made of such subjects as powder *x* ray diffraction techniques, the electron probe, or geochemical and geobotanical prospecting, among others. This is a minor criticism—the authors have done an excellent job on a number of the most important methods. The book can be recommended both to practitioners of the methods covered, and to geologists who would like to know what laboratory techniques can be usefully applied to their problems.

C. L. CHRIST
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Washington 25, D. C.

METHODS AND TECHNIQUES IN GEOPHYSICS, VOLUME I. Edited by S. K. Runcorn, 374 pages, Interscience Publishers, 250 Fifth Avenue, New York, N. Y., 1960. Price: $10.00.

The discussions in Volume I of this series treat subjects that are of primary interest to investigators dealing with the solid earth. Methods of making measurements are stressed. Each section includes a discussion of the particular difficulties that are encountered in making measurements and some theory of the instruments employed. Illustrations in the form of line drawings and half-tone prints have been included generously. Each author had produced a condensation from a diversified bulk of publications. References at the end of each chapter will be of great value to anyone wishing to pursue the types of measurement under discussion.

Each chapter has been written to stand alone as an introduction to measurements in a particular phase of geophysics. This causes a lack of continuity from chapter to chapter. The subjects treated, with their respective authors, are: "Measurement of Temperature Gradient in the Earth," by E. C. Bullard; "The Measurement of Heat Flow over Land," by A. D. Misener and A. E. Beck; "Bore-hole Surveying," by T. Gaskell; "Measurement of the Geomagnetic Elements," by K. Whitham; "Measurements in Paleomagnetism," by D. W. Collinson and K. M. Creer; "The Measurement of Gravity at Sea," by J. C. Harrison; "The Detection of Earth Movements," by P. L. Willmore; "Earth Currents," by G. D. Garland; "Properties of Rocks under High Pressure and Temperature," by D. S. Hughes; "Latitude and Longitude, and the Secular Motion of the Pole," by W. Markowitz.

John DeNoyer
Department of Geology
The University of Michigan

CRYSTAL-STRUCTURE ANALYSIS, by Martin J. Buerger. John Wiley and Sons, Inc., New York. xvii plus 668 pages, 329 figs. 1960. Price $18.50.

This book is a very complete description of the various phases of crystal structure determination, as shown by the Chapter headings, as follows:

Fundamental diffraction relations
Quantitative aspects of x-ray diffraction
Outline of a crystal structure analysis
Selection of material
Measurement of intensities. Geometrical and Physical factors affecting intensities
Number and distribution of atoms in the unit cell
The Structure Factor. Plane projections in structure-factor calculations
Examples of the determination of some simple structures
Fourier synthesis, general theory. Useful forms of Fourier synthesis
Reciprocal Space. Symmetry in reciprocal space
Applications of symmetry to Fourier summations
Practical methods of summing Fourier series
Phase determinations for structures having heavy or replaceable atoms. Phase determinations for certain special cases. Direct determination
Refinement of structure
Calculation of interatomic distances and angles.

There are numerous illustrations and tables, and there is a list of references at the end of each chapter.

The reviewer knows of no other single publication in which such a large amount of pertinent information is available. The author has thus added one more item to the already long list of his important contributions to the field of crystal structure determinations.

Lewis S. Ramsdell
Mineralogy Department
University of Michigan

ADVANCES IN *X* RAY RESEARCH, Vols. 1, 2 and 3. Edited by William M. Mueller. Distributed by Plenum Press, Inc., N. Y. Prices: Vols. 1 and 2, $8.50 domestic, $10.00 foreign, Vol. 3, $12.00 domestic and foreign.

These three volumes represent the Proceedings of the 6th, 7th and 8th Annual Conferences on Application of *X* ray Analysis, sponsored by the Denver Research Institute, University of Denver, for the years 1957, 1958 and 1959. The papers presented, with illustrations are included in these volumes as follows: Vol. 1, 32; Vol. 2, 26, and Vol. 3, 25 papers.

TEN MORE YEARS OF NEW MINERAL NAMES

Michael Fleischer

Ten years ago (*Am. Mineral.*, **36**, 630 (1951)), I summarized ten years of abstracting new mineral names. The table below is a similar summary of the abstracts in Volumes 36 through 45 of the *American Mineralogist.* These are, of course, my opinions of the names proposed, and many of them are subject to argument.

The most obvious points are that new names are being proposed at a rate more than double that of the preceding ten years, but that the percentage that seem to be valid (56 per cent) is not much improved over the previous decade (47 per cent). More than ever, restraint and care in proposing new names is necessary to keep the science from being swamped.

	Total new names proposed	Valid names	Identical with known minerals	Unnecessary names for varieties	Insufficient data	Minerals discredited
1951	61	15	40	6	0	13
1952	27	16	8	2	1	12
1953	18	16	1	1	0	7
1954	29	22	1	3	3	31
1955	40	21	4	9	6	7
1956	38	27	9	2	0	5
1957	42	23	4	10	5	25
1958	53	31	6	13	3	15
1959	54	31	5	7	11	20
1960	57	32	6	11	8	4
	419	234	84	64	37	139
1941–1950	164	77	22	33	32	85

NEW MINERAL NAMES

Schoderite, Metaschoderite

D. M. Hausen. Schoderite, a new phosphovanadate mineral from Nevada. *Bull. Geol. Soc. Am.*, **71,** 1883 (1960) (abstract).

The mineral occurs as yellowish-orange microcrystalline coatings associated with wavellite and vashegyite along fractures in phosphatic chert near Eureka, Nevada. It is in microscopic monoclinic, bladed tabular crystals, elongated parallel to (001). Unit cell dimensions a 11.4, b 15.8, c 9.2 A., beta 79°. The strongest x-ray lines are 2.79–10, 9.6–10, 11.1–5, 15.8 A.–4. It is biaxial, positive, alpha 1.542, beta 1.548, gamma 1.566, 2V (calcd) 60°, $\gamma = b$. Formula $2Al_2O_3 \cdot P_2O_5 \cdot V_2O_5 \cdot 16\,H_2O$.

At room temperature in a dry atmosphere, the mineral dehydrates to metaschoderite, $2Al_2O_3 \cdot V_2O_5 \cdot P_2O_5 \cdot 12H_2O$. This rehydrates to schoderite on contact with water. Metaschoderite has the same a, c, and beta as schoderite, but b shrinks to 14.9 A. Biaxial, positive (given as negative), α 1.598, β 1.604, γ 1.626, 2V 73° (calcd.), $Z = b$. The strongest x-ray line are 7.5–10, 14.9–6, 11.1–5, 3.02 A.–3.

The name is for William P. Schoder, research chemist, Union Carbide Nuclear Co.

Discussion.—Presumably to be classed with the aluminum vanadates steigerite and al'vanite.

Michael Fleischer

Unnamed Pt and Pd minerals

I. B. Borovskii, A. N. Deev, and I. D. Marchukova. Application of the method of local x-ray spectrographic analysis to the study of minerals of the platinum group. *Geol. Rudnykh Mestorozhdenii* **1959,** No. 6, 68–73 (in Russian).

A. D. Genkin. Conditions of occurrence and features of the composition of minerals of the platinum group in the Noril'sk deposits. *Ibid.*, 74–84 (in Russian).

Platinum minerals of the Noril'sk deposits were studied optically and analyzed by means of an electron probe. The following minerals appear to be new:

Mineral No. 5. Analysis gave Pd ~ 70, Pb ~ 30, Ag ~ 1%, corresponding approximately to Pd_4Pb. Occurs in chalcopyrite and cubanite as elongated crystals and fills interstices in sperrylite. Brownish tint. Reflecting power 65%. Weakly anisotropic. Relief less than that of platinum and sperrylite, greater than that of cubanite. Blackened by aqua regia, not etched by concd. HCl or HNO_3.

Mineral No. 8. Analysis gave Pd58, S ~ 40, approximating PdS_2. X-ray diagram (not given) stated to be similar to that of braggite (Pt, Pd, Ni)S. Reflecting power low, 44 45%. Weakly anisotropic, hardness medium, scratched by steel, microhardness 32 kg/sq.mm. Relief greater than that of chalcopyrite or millerite. Not etched by aqua regia or concentrated acids.

Mineral No. 6.—Analysis gave Pt ~ 36, As ~ 28, Ru ~ 3%; it is not known what element is missing, perhaps osmium which could not be determined. In small (0.02–0.05 mm.) isometric crystals. Grayish-white, low reflecting power. Hardness and relief highest of all Pt minerals. Perhaps an osmian sperrylite?

Data are also given for two alloys of Pt (Minerals No. 1 and 3) containing Pt 82–86.5, Sn ~ 8, Ir ~ 5, Pd ~ 2, Fe 0.5%, and Pt 75–76.4, Fe ~ 10, Ir ~ 6–8, Ni ~ 3–4, Cu and Ag < 1%; sperrylite (Mineral No. 4) containing Pt 60–63, As 40, Sn 2–4, Rh ~ 1%, stibiopalladinite (Mineral No. 7) containing Pd ~ 73, Sb 25%, and a mineral, perhaps near stannopalladinite (Mineral No. 2) containing Pd 28, Pt ~ 50, Sn ~ 30, Ir ~ 2.5%.

M. F.

Niobozirconolite

. S. Borodin, A. V. Bykova, T. A. Kapitonova, and Yu A. Pyatenko. New data on zirconolite and its niobian variety. *Doklady Akad. Nauk. S.S.S.R.* **134,** 1188–1191 (1960) (in Russian).

Two new analyses are given of zirconolite (AB_3O_7, nearly $CaZrTi_2O_7$, see *Am. Mineral.* **22,** 581 (1957). One of these, from apatite-magnetite rocks of the Vuorijarvi massif, Kola Peninsula, is called niobozirconolite. Analysis by A. V. B. gave $TiO_2$18.19, Nb_2O_5 24.84, Ta_2O_5 2.00, Fe_2O_3 1.11, ZrO_2 25.00, U_3O_8 0.40, ThO_2 2.90, Ce_2O_3 4.00, CaO 11.00, FeO .00, MnO 0.38, Na_2O 1.40, H_2O 2.48, F 0.60, sum 100.30—($O=F_2$) 0.25=100.05%. This corresponds to $(Ca, Zr, Fe^{+2})_2\ (Ti, Nb, Zr)_2O_7$ with Ca:Zr about 1:1 and Ti:Nb=6:5. 4.51. Unit cell of cubic phase (presumably after heating M.F.).=5.03 A. This may be intermediate between zirconolite and pyrochlore, $Ca\ Na\ Nb_2\ (O, F)_7$, but further study is required.

Discussion.—Unnecessary name for niobian zirconolite.

M. F.

Lazarevićite

C. B. Sclar and Matija Drovenik. Lazarevićite, a new cubic copper-arsenic from Bor, Jugoslavia. *Bull. Geol. Soc. Am.*, **71,** 1970 (1960) (abstract).

The mineral occurs as microscopic grains in copper ore from the Tilva Mika deposit, Bor, eastern Serbia. It is associated with enargite, luzonite, covellite, and pyrite. An electron-microprobe analysis gave Cu 52.5, As 12.5, Fe 1.9%. This with spectrochemical analysis leads to the formula $Cu_3\ (As_{0.65}Cu_{0.22}Fe_{0.13}V_{tr.})S_4$, ideally Cu_3AsS_4. Cubic, space group *P*43*m*, a_0 5.28±0.01 (not stated whether A or kX), Z=1, G. calcd. 4.39.

The name is for M. Lazarević, pioneer investigator of the geology and ore deposits of Bor, 1908–1913.

Discussion.—The name arsenosulvanite (see *Am. Mineral.*, **40,** 368–369 (1955)) was given to $Cu_3(As, V)S_4$ with As:V=2:1. I would have preferred to see this name extended to the As end number, so that the series could be described in terms of two names only.

M. F.

Paulite, Ellweilerite

F. W. Bültemann. Die Uranmineralien vom Bühlskopf bei Ellweiler, Kreis Birkenfeld/Nahe. *Der Aufschluss,* **11,** No. 11, 281–283 (1960).

The U deposit occurs in weathered porphyry. Minerals identified include pitchblende, coffinite (?), zeunerite, boltwoodite, curite, and two new minerals. Paulite forms very thin tablets, light yellow, transparent, strongly fluorescent under U. V. It is partly intergrown with zeunerite. Microchemical tests were obtained for Al, U, and As; it is suggested that is the As-analogue of sabugalite, $HAl(UO_2)_2(PO_4)\cdot 16H_2O$. Ellweilerite occurs with zeunerite and partly intergrown with it. In thin tabular crystals and flaky aggregates, light yellow to nearly water-clear. Fluoresces very strongly in short- and long-wave U.V. Microchemical tests showed Na, U, and As. The d-values (not given) are stated to agree well with those of Mrose (*Am. Mineral.*, **38,** 1159–1168 (1953) on synthetic Na analogue of uranospinite.

The names are for Hans Paul, Gewerkschaft Brunhilde, and for the locality.

Discussion.—The name sodium uranospinite has already been given to ellweilerite *Am. Mineral.*, **43,** 383–384 (1958)); the author considers the new name to be justified because the previously described material contained some calcium. I do not agree. The ame paulite has been used for hypersthene (Dana's System, 6th Ed., p. 348) and is also easily confused with pallite (see *Am. Mineral.*, **45,** 256–257 (1960)). But above these considerations, names should not be given to minerals with such inadequate descriptions.

M. F.

Baotite (=Pao-t'ou-Kuang)

V. I. Simonov. Baotite, a mineral with a metasilicate ring (Si_4O_{12}). *Kristallografiya*, **5,** 544–546 (1960) (in Russian).

A preliminary note on this mineral was abstracted in *Am. Mineral.*, **45,** 754 (1960). In the Russian paper, the name is transliterated baotite. The formula is given as $Ba_4(Ti,Nb)_8ClO_{16}(Si_4O_{12})$.

M. F.

Garronite

G. P. L. Walker. The amygdale minerals in the Tertiary lavas of Ireland. III. Regional distribution. *Mineralog. Mag.* v. **32,** 503–527 (1960).

The information given is, "The list includes a probable new zeolite, related to phillipsite, for which the name 'garronite' is tentatively suggested."

Discussion.—Names should not be given without descriptions; the mineral should have been referred to as a possibly new zeolite, without a name.

M. F.

Loughlinite

J. J. Fahey, Malcolm Ross, and J. M. Axelrod. *Am. Mineral.*, **45,** 270–281 (1960).

Papagoite

C. O. Hutton and A. C. Vlisidis. *Am. Mineral.*, **45,** 599–611 (1960).

Paratellurite

George Switzer and H. E. Swanson. *Am. Mineral.*, **45,** 1272–1274 (1960).

Paulingite

W. B. Kamb and W. C. Oke. *Am. Mineral.*, **45,** 79–91 (1960).

Ranquilite

M. J. de Abeledo, M. R. de Benyacar, and E. E. Galloni. *Am. Mineral.*, **45,** 1078–1086 (1960).

Reedmergnerite

Charles Milton, E. C. T. Chao, and J. M. Axelrod. *Am. Mineral.*, **45,** 188–199 (1960).

Weeksite

W. F. Outerbridge, M. H. Staatz, R. Meyrowitz, and A. M. Pommer. *Am. Mineral.*, **45,** 39–52 (1960).

NEW DATA

Teineite

Anna Zemann and J. Zemann. Zur Kentniss des Teineits: *Beitr. Mineral. u. Petrog.*, **7,** 436–438 (1960).

Teineite has been considered to be $Cu_{13}(SO_4)_3(TeO_4)_{10}\cdot 26H_2O$ or perhaps Cu[(Te,

$)O_4]\cdot 2H_2O$ (Dana's System, 7th Ed., **2**, 635–636). Weissenberg study of type material hows it to have space group $P\ 2_12_12_1$; the unit cell has *a* 6.63, *b* 9.61_5, *c* 7.43_3 Å. These re so close to the data for chalcomenite, $CuSeO_3\cdot 2H_2O$, that it is probable that teineite a tellurite, and not a tellurate.

The sp. gr. calculated for $CuTeO_4\cdot 2H_2O$ is 4.08, for $CuTeO_3\cdot 2H_2O$ is 3.85, determined .80. (But if the S shown in the analysis is included, the calculated sp. gr. is far too low; new analysis is needed. M.F.)

M. F.

Eskebornite

ERHARD TISCHENDORF. Über Eskebornit von Tilkerode im Harz: *Neues Jahrb. Mineral., Abhandl.*, **94** (Ramdohr Festband), 1169–1182 (1960).

The formula of eskebornite has been given as FeSe and Fe_3CuSe_4. Two analyses of ynthetic preparations with a_0 5.53–5.55 A. (for natural material a_0 5.53_5 A.) gave $u_{0.43}Fe_{0.61}Se$ and $Cu_{0.55}Fe_{0.62}Se$, and an *x*-ray fluorescence analysis of another synthetic preparation gave $Cu_{0.55}Fe_{0.55}Se$. The general formula may be $(Cu, Fe)_{1.1}Se$. *X*-ray powder ata are given.

M. F.

Koutekite

DENEK JOHAN. Koutekit—Cu_2As, ein neues Mineral. *Chem. der Erde*, **20**, 217–226 (1960).

A preliminary note was abstracted in *Am. Mineral.*, **43**, 794 (1958). New data given: uster metallic, streak black. Hardness 4–4½. *X*-ray powder data are given for the mineral; hey are identical with those for synthetic Cu_2As and are clearly different from those of domeykite. The pattern is indexed on a hexagonal cell with *a* 11.51, *c* 14.54 Å. The trongest lines are 2.078 (10)(142), 2.024 (10)(126), 1.994 (10)(050), 1.147 (9)(085), 1.324 5)(170), 1.197 (8)(266,272), 1.178 (8)(084), 2.446 (7)(041), 1.374 (7)(261)(443), 3.33 6)(030), 1.785 (6)(333). A perfect cleavage in one direction was noted in a synthetic reparation. Koutekite is replaced by an unknown copper arsenide and by löllingite.

M. F.

DISCREDITED MINERALS

Gajite (=Calcite+Brucite)

J. BARIC. Gajit, ein Gemenge von Calcit und Brucit. *Neues Jahrb. Mineral., Abhandl.*, **94** (Ramdohr Festband), 1200–1202 (1960).

Gajite, described in 1911 (Dana's System, 7th Ed., vol. II, p. 264), was found by ptical and *x*-ray study to be a mixture of calcite and brucite.

M. F.

Deltaite (=Crandallite+Hydroxylapatite)

W. T. ELBERTY AND S. S. GREENBERG. Deltaite is crandallite plus hydroxylapatite. *Bull. Geol. Soc. Am.*, **71**, 1857 (1960) (abstract).

X-ray study of deltaite (Dana's System, 7th Ed., p. 837) indicates it to be a mixture.

M. F.

Delatorreite (=Todorokite)

C. FRONDEL, U. B. MARVIN AND J. ITO. *Am. Mineral.*, **45**, 1167–1173 (1960).

J. A. STRACZEK, ARTHUR HOREN, MALCOLM ROSS, AND C. M. WARSHAW. *Am. Mineral.*, **45**, 1174–1184 (1960).

Lesserite (=Inderite)

W. T. Schaller and M. E. Mrose. *Am. Mineral.*, **45,** 732–734 (1960).

Pilinite (=Bavenite)

George Switzer and L. E. Reichen. *Am. Mineral.*, **45,** 757–762 (1960).

Woodfordite (=Ettringite)

Joseph Murdoch and R. A. Chalmers. *Am. Mineral.*, **45,** 1275–1278 (1960).

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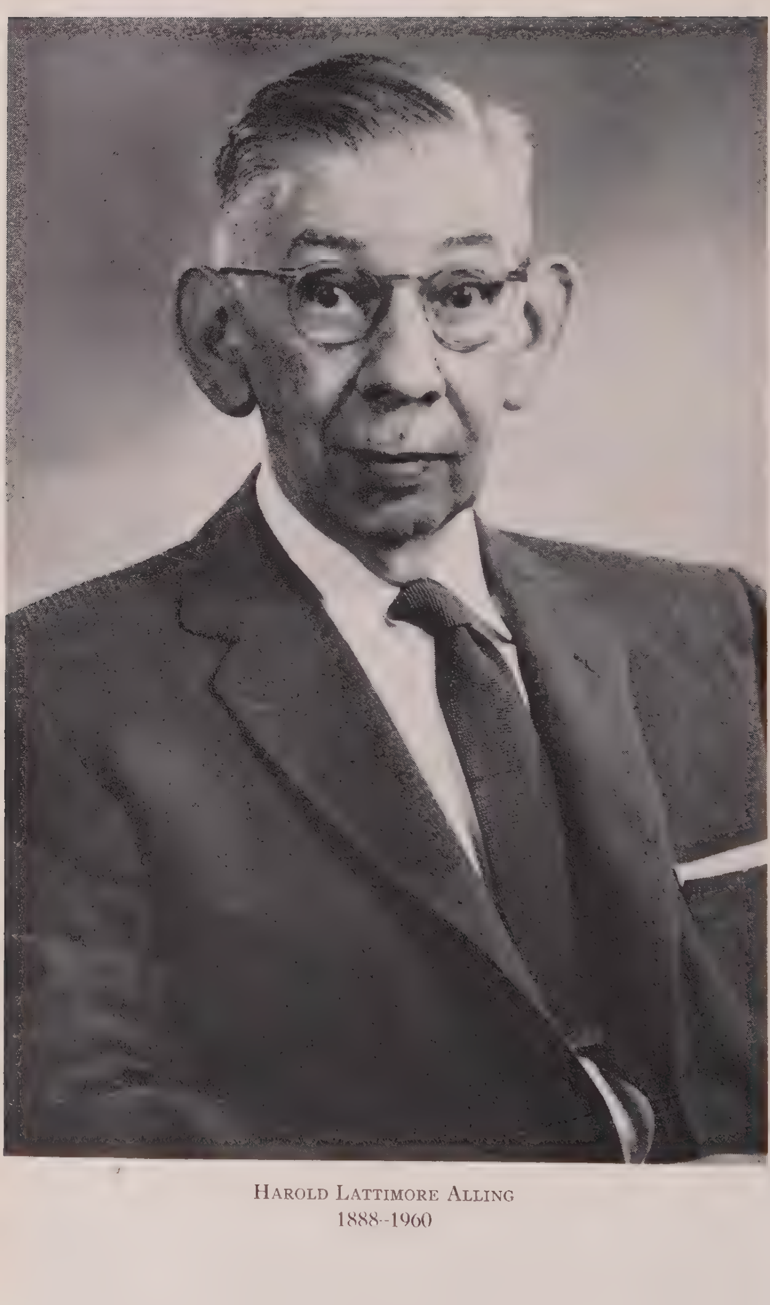

Harold Lattimore Alling
1888–1960

THE AMERICAN MINERALOGIST, VOL. 46, MARCH-APRIL, 1961

MEMORIAL OF HAROLD LATTIMORE ALLING

DAVID E. JENSEN, *Ward's Natural Science Establishment, Inc., Rochester, New York*

Harold Lattimore Alling, former Vice-President of our society, passed away at his home in Pittsford, New York on July 27, 1960. Though he had been hospitalized with cancer for several weeks, he was able to review a part of the manuscript of his latest papers two days before he died.

The son of Joseph Tilden Alling and Rose Lattimore, he was born in Rochester, New York on Feburary 7, 1888. His grandfather on his mother's side, Samuel Allan Lattimore, was Professor of Chemistry in the University of Rochester for forty-two years. His father was for many years Chairman of the University's Board of Trustees.

After graduation from Rochester's East High School, he entered the University of Rochester where he first became especially interested in physics, taking advanced work in addition to all of the available courses. At the suggestion of his grandfather, Professor Lattimore, he diverted his chief interest to geology and in 1915 he received his B.S. degree from the university with honors in geology.

The Alling family used to spend their summers at their camp near Keene Valley in the Adirondack mountains. It was quite natural, therefore, that, with the stimulating guidance of Professor H. L. Fairchild, Harold Alling's first published paper would be on glacial lakes and other glacial features of the central Adirondacks.

One summer he learned that Professor James Kemp of Columbia University was doing field work near Keene so he volunteered his services as Professor Kemp's field assistant. This association firmly established a lively and lasting interest in the geology of the Adirondack region. It also influenced him to enter Columbia University for graduate work. There he studied under Professors Kemp, Berkey, and Colony obtaining his A.M. degree in 1917 and his PhD. in 1920.

From 1917 to 1920 he served as geologist for the New York State Museum. During the first world war, he was engaged in the investigation of war materials under the direction of the National Research Council. A thorough survey of the Adirondack graphite deposits was made in the course of this work in the summer of 1917. The results of this study were published as a bulletin of the New York State Museum in 1918.

The graphite studies could have adequately served for his doctorate at Columbia University but he had become intensely interested in the physical chemistry of the feldspars. Thus the mineralography of the feldspars became the topic of his doctorate.

In 1920 Dr. Alling returned to the University of Rochester as instructor in geology, advancing to assistant professor in 1923 and becoming professor in 1924, and chairman of the Geology Department from 1924 to 1946. He retired in 1953. He had a large part in the planning of the geology wing of the Chester Dewey Building on the River Campus of the University which was opened to students in the fall of 1930. Many of the good features of this building were soon sought for incorporation in geology departments elsewhere in the country.

Dr. Alling was an inspiring teacher. He had the facility of using simple, everyday examples to get a point across. He was especially generous with his time and knowledge in helping graduate students and often aided them financially. He was a tireless researcher in the field and in the laboratory. His contributions to geologic literature number over 45 papers and books. He was an enthusiastic photographer and made hundreds of photomicrographs of minerals and rocks that often illustrated his publications.

From 1931 to 1940 Dr. Alling was a Director of Ward's Natural Science Establishment, Inc. To this post he brought wise counsel and suggestions for the development of teaching aids. Along the latter was a series of geomorphological models which are being used in teaching elementary geology in all parts of the world.

He was a Fellow of the Mineralogical Society of America and served as its Vice-President in 1936. He was a Fellow and Life Member of the Rochester Academy of Science serving as Secretary in 1920–1921. From 1927 to 1932 he was Chairman of the Feldspar Committee of the National Research Council; Trustee of the Natural Science Association of the Catskills, 1945 1949; and Director of the Alling & Cory Co., 1938–1945; Fellow, American Geophysical Union.

His scientific affiliations were numerous. He was a Fellow of the American Association for the Advancement of Science, the Geological Society of America, and the New York Academy of Science. He was a member of the Seismological Society, the Society of Economic Paleontologists and Mineralogists, New York State Geological Association (President 1932, 1941), American Institute of Mining, Metallurgical and Petroleum Engineers, the Geochemical Society, and the Rochester Section, American Chemical Society, and the New York State Archeological Society. He was a member of Psi Upsilon and Sigma Xi.

On August 23, 1922, he married Merle Kolb who survives with three children, Joanna Tilden (Mrs. James D. Secrest), Rosamund Lattimore (Mrs. Philip J. Secrest) and Norman Larrabee Alling.

BIBLIOGRAPHY OF HAROLD LATTIMORE ALLING

1916 Glacial Lakes and other glacial features of the Central Adirondacks: *Bull. Geol. Soc. Am.*, **27,** 645–672.

1918 Descriptive catalog of a petrographic collection of rocks from Cripple Creek, Colorado: Ward's Natural Science Establishment.

1918 The Adirondack Graphite Deposits: *N. Y. State Mus. Bull.* **199,** 1–150.

1919 Some problems of the Adirondack Precambrian: *Am. Jour. Sci.* (4), **48,** 47–68.

1919 The Geology of the Lake Clear region: *N. Y. State Mus. Bull.* **207–208,** 111–145.

1920 Pleistocene geology of the Lake Placid Quadrangle: *N. Y. S. Mus. Bull.* **211–212,** 71–95.

1921 The Mineralography of the Feldspars, Part I; *Jour. Geol.*, **29,** 193–294.

1921 The origin of graphite: *Econ. Geol.*, **16,** 334–337.

1921 Graphite: *N. Y. S. Mus. Bull.* **223–224,** 85–95.

1921 Pleistocene geology of the Mt. Marcy Quadrangle: *N. Y. S. Mus. Bull.* **229–230,** 62–84.

1923 The Mineralography of the Feldspars, Part II: *Jour. Geol.*, **31,** 282–305.

1924 The origin of the foliation and the naming of Synthetic rocks: *Am. Jour. Sci.* (5), **8,** 12–32.

1925 Geology of the Ausable quadrangle: *N. Y. S. Mus. Bull.* **261,** 5–124 (with James Kemp).

1926 Four recent papers on the feldspars: *Am. Mineral.*, **11,** 105–107.

1926 The Potash-Soda Feldspars: *Jour. Geol.*, **34,** 1927, 591–611.

1927 Quantitative microscopic analysis: *Am. Jour. Sci.*, **14,** 50–65 (with W. G. Valentine).

1927 The stratigraphy of the Grenville of the Eastern Adirondacks: *Geol. Soc. Am. Bull.*, **38,** 795–804.

1928 The Geology and Origin of the Silurian salt of New York State: *N. Y. S. Mus. Bul.* **275,** 5–139.

1928 A porphyritic monzonitic bentonite: *16th Bien. Rept., Vermont State Geologist*, 290–291.

1929 The Genesis of some types of feldspar from granite pegmatites (with Olaf Anderson abstract by H. L. Alling): *Am. Mineral.*, **14,** 241–242.

1929 The indices of refraction of the plagioclase feldspars: *Jour. Geol.*, **37,** 462–482.

1929 Falcon Island: *Am. Jour. Sci.*, **18,** 461–471 (with J. Edward Hoffmeister and Harry S. Ladd).

1929 The ages of the Adirondack gabbros: *Am. Jour. Sci.*, **18,** 472–476.

1930 Feldspars in the Adirondack anorthosite: *Am. Mineral.*, **15,** 267–271.

1932 Perthites: *Am. Mineral.*, **17,** 43–65.

1932 The Adirondack anorthosite and its problems: *Jour. Geol.*, **11,** 193–237.

1933 The position of the cotectic line between potash feldspar and plagioclase and their relations: *Am. Jour. Sci.*, **25,** 471–476.

1933 Quantitative microscopic methods: *Econ. Geol.*, **28,** 695–696.

1933 Petrography of the igneous rocks of Eua, Tonga: *Bernice P. Bishop Mus. Bull.* **96,** 39–49.

1936 Interpretative petrology of the Igneous Rocks: McGraw-Hill Book Co., Inc., New York, 353 pages.

1936 Petrology of the Niagara Gorge sediments: *Proc. Rochester Acad. Sci.*, **7,** 189–207.

1938 Plutonic perthites: *Jour. Geol.*, **46,** 142–165.

1938 Geology (Part I) and Geology (Part II) in "An Orientation in Science," McGraw-Hill Book Co., Inc., New York, p. 84–116, 239–255. With C. W. Watkeys, Editor, and others.

1939 Metasomatic origin of the Adirondack magnetite deposits: *Econ. Geol.*, **34,** 141–172.

1940 Review. Adirondack igneous rocks and their metamorphism (A. F. Buddington): *Am. Mineral.*, **25,** 305–307.

1941 A Diaphragm Method for grain size analysis: *Jour. Sed. Petrology*, **11,** 28–31.

1942 The Adirondack magnetite deposits in "Ore Deposits as related to structural features": Princeton Univ. Press, p. 143–146.

1943 A metric grade scale for sedimentary rocks: *Jour. Geol.*, **51,** 259–269.

1944 Grain analysis of minerals of sand size in ball mills: *Jour. Sed. Petrology.*, **14,** 103–114.

1945 Petrography of igneous rocks in "Geology of Lau, Fiji," *Bernice P. Bishop Mus. Bull.* **181,** p. 191–202. With Harry S. Ladd, J. Edward Hoffmeister, and others.

1945 Use of Microlithologies as illustrated by some New York sedimentary rocks: *Bull. Geol. Soc. Am.*, **56,** 737–756.

1946 Quantitative petrology of the Genesee Gorge sediments: *Proc. Rochester Acad. Sci.*, **9,** 5–63.

1947 Diagenesis of the Clinton hematite ores of New York: *Geol. Soc. Am. Bull.*, **58,** 991–1018.

1950 Initial shape and roundness of sedimentary rock mineral particles of sand size: *Jour. Sed. Petrology*, **20,** 133–147.

1951 Abrasion of nine minerals of sand size in ball mills: *Am. Jour. Sci.*, **249,** 569–590.

1959 Cayugan of eastern United States: *Geol. Soc. Am. Bull.*, **70,** 1561 (with L. I. Briggs).

1961 Stratigraphy of the Upper Silurian Cayugan evaporites: *Am. Assoc. Petrol. Geol. Bull.*, **45,** April 1961 (In Press) (with L. I. Briggs).

1961 Petrology of the Salina sediments of New York: *Am. Assoc. Petrol. Geol. Bull.* (Submitted for publication).

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MEMORIAL OF CIRO ANDREATTA

PAOLO GALLITELLI, *Università di Bologna, Bologna, Italy*

Ciro Andreatta died on Feburary 6, 1960 after a short illness. He was Professor of Mineralogy at the University of Bologna, and a Fellow of the Mineralogical Society of America. He was born in Pergine in the Province of Trento on January 23, 1906, and graduated from University of Padova in 1928 with a degree in Natural Sciences. He remained there as a graduate student (1929) and as an assistant (1930–1936) in the department of Mineralogy and Petrography.

In 1932 he became a docent in Mineralogy and attended for a year the Institute of Mineralogy and Petrography at the University of Innsbruck, where under the guidance of Bruno Sander, he studied the fundamental principles of modern structural rock analyses while also undertaking some original research of his own. In 1936 he was appointed Professor of Mineralogy at the University of Messina where he remained until he was called to the Chair of Mineralogy at the University of Bologna in 1938. He remained there without interruption till his premature death. He participated intensely in scientific activities, and from 1953 on directed the "Centro di Petrotettonica" of the National Council of Research. In 1959 he was elected chairman of the Science Department at the University. In the years between 1938 and 1959 there were also other executive responsibilities: he was the representative of the academic faculty in the University's Administrative Council. For his scientific merits, the National Academy of Lincei awarded him with the National Prize for Mineralogy in 1951. He was correspondent of the National Academy of Lincei, of the Academy of Science in Vienna and of the Geological Society of America; he was a Fellow of the Mineralogical Society of America; a member of the Mineralogical Society of London, of the Deutschen Mineralogischen Gesellschaft, of the Swiss Society for Mineralogy and Petrografy and of the Società Mineralogica Italiana of which he was also a President from 1955 to 1957. He was the Italian delegate in the "New Minerals" Commission of the International Mineralogical Association.

His scientific activity, as represented in more than one hundred publications, began in 1928 with a series of research studies on Alpine minerals, such as chalcopyrite, pickeringite, and arsenopyrite (of this he described some rare twins). Others studies concerned bianchite, a new hydrated sulfate of iron and zinc, which was observed for the first time in the caves of Predil, and dannermoite in the Valley of Peio.

However, Professor Andreatta performed the major part of his vast and intense studies in the petrographical research field where he emerged

Ciro Andreatta
1906–1960

as a master because of his brilliant qualities of observation as well as his profound knowledge of the optical phenomena of minerals. These qualities enabled him to solve through modern criteria many geological and petrographical problems and also develop applications of Sander's petrotectonics of which he was the most qualified expounder in Italy.

His first petrographical works, among which a noteworthy one is "Ricerche Petrografiche sulla regione di Cima d'Asta," were followed by a large amount of research regarding the orientation of various minerals in metamorphic rocks. On the basis of this he established the orientation rule of olivine, cyanite, and anhydrite, of the "formazione dioritica Kinzigitica" of Val d'Ultimo and the crystaline rocks of Peloritani. But his most significant contribution was the series of studies regarding rocks of the Ortles Mountain area, extending for approximately 1800 square kilometers and containing mountain peaks close to 4000 meters high, of which he had completed a geological and petrographical survey and on the basis of which he succeeded in solving with modern criteria geological and petrographical problems using with originality the concepts of Petrotectonics. Within this general line of inquiry must be mentioned his work on polymetamorphism, as well as on the mobilization and on the movements of matter which accompany tectonic metamorphism, and on the phenomena of granitization. In the last few years he had been actively working on other research projects, some of which have not yet been completed. Among these is the study of the porphyritic formations of Val d'Adige—a work on which he left numerous manuscripts, chemical analyses and observations which testify to his intense activity in this area.

Other works concern the clay minerals of Puglie, in the area of Viterbo, on the Vicenza Alps, and on the mechanism of reticular degradation of feldspar and the transformation of mica into montmorillonite through hydromica. Finally there are some studies of ore deposits in the region of Venezia Tridentina; in these studies the late Professor Andreatta indicates very clearly the genesis of these ores, with regard to the geological history of the imbedded rock formation.

Worthy of mention is also the excellent text book of mineralogy and crystallography prepared for the students attending the courses of natural and geological sciences; this volume undoubtedly has high place among Italian texts on mineralogy.

These are briefly the great merits of Ciro Andreatta which put him in a high place among contemporary Italian mineralogists. But those who have known him cannot forget that in addition to being a valiant and good scholar he was also a good, simple and reserved man who spoke rarely, but always incisively—the man who was close to his family.

A man who was so sensitive that in the moments of solitude he could portray his mountains of Trentino with a paint brush. He was the tireless man who was able to inspire enthusiasm and affection in his numberless students who will always remember him with high regard.

SELECTED BIBLIOGRAPHY OF CIRO ANDREATTA

Sull'arsenopirite di Nogarè (Trentino): *Studi Trentini di Scienze Naturali*, **9,** 139–148, 1928.

Sulle arsenopiriti dei giacimenti minerari di Calceranica e Caldonazzo nel Trentino: *Ibid.* **9,** 90–102, 1928.

Di un'interessante roccia filoniana dei Laghi d'Aje nel Lagorai (Trentino): *Ibid.* **9,** 173–184, 1928.

Pickeringite di Canezza (Trentino): *Ibid.*, **11,** 62–68, 1930.

Bibliografia Mineralogica della Venezia Tridentina: *Archivio per l'Alto Adige*, **23,** 1–44, 1929.

Su alcune calcopiriti della Venezia Tridentina: *Atti dell'Accademia Veneto Trentino-Istriana;* **20,** 21–28, 1929.

Alcuni interessanti filoni nella massa intrusiva di Cima d'Asta. *Atti del R. Istituto Veneto di Scienze, Lettere ed Arti*, **89,** 827–862, 1930.

Bianchite, nuovo minerale. *Rend. della R. Accad. Nazionale dei Lincei, Classe di Sc. fis. mat. e nat.*, **11,** 760–769, 1930.

Ricerche petrografiche sulla Regione di Cima d'Asta. *Memorie dell'Istituto Geologico della R. Università di Padova*, **10,** 1–62, 1932.

Nuove ricerche sulla bianchite: bianchite sintetica. *Rendiconti della R. Accademia Nazionale dei Lincei, Classe di Sc. fis., mat. e nat.*, **16,** 62–69, 1932.

Analisi strutturali di rocce metamorfiche, I. *Periodico di Mineralogia*, **3,** 181–196, 1932.

Analisi strutturali-di rocce metamorfiche, II (Quarzo-tettoniti). *Ibid.* **4,** 15–24, 1933.

Analisi strutturali di rocce metamorfiche, III. La disposizione dei microliti micacei nei plagioclasi di ortogneis. *Ibid.* **4,** 375–293, 1933.

Disposizione dei microliti micacei in plagioclasi di rocce intrusive. (Analisi strutturali di rocce, IV). *Ibid.*, **5,** 217–235, 1934.

Analisi strutturali di rocce metamorfiche, V. Oliviniti. *Ibid.*, **5,** 237–253, 1934.

La formazione gneissico-kinzigitica e le oliviniti di Val d'Ultimo (Alto Adige). "*Memorie del Museo di Storia Naturale della Venezia Tridentina*," **5,** 87–245, 1936.

Analisi strutturali di rocce metamorfiche, VI: Regola d'orientazione della cianite. *Periodico di Mineralogia*," **6,** 205–212, 1935.

Ueber die quantitative mineralogische Klassifikation der Eruptivgesteine und ihre diagrammatische Darstellung. *Zentralblat' für Mineralogie*, 303–314, 321–343, 1937.

Studio petrografico del complesso eruttivo del Monte Croce in Alto Adige. "*Periodico di Mineralogia*, **8,** 311–446, 1937.

Basalti della Valle dell'Alpone e loro inclusi peridotitici. *Bollettino della Società Geologica Italiana*, **57,** 239–264, 1938.

Giacimenti di granato almandino ai contatti del massiccio intrusivo di Cima D'Asta e loro paragenesi. "*Studi Trentini si Scienze Naturali*," **19,** 105–134, 1938.

Analisi strutturali di rocce metamorfiche. VII: anidrite. *Periodico di Mineralogia*, **9,** 305–321, 1938.

Sui cosidetti "Scisti del Verrucano" dell' Alto Adige occidentale. *Studi Trentini di Scienze Naturali*, **20,** 213–253, 1939.

I giacimenti ferriferi della regione Boai-Comasine in Val di Peio (Trentino). *La Ricerca Scientifica*, **10,** 515–531, 1939.

Appunti geologico-petrografici su alcuni problemi dello zoccolo cristallino dell'Eritrea. *Rendiconti della R. Accademia d'Italia, Classe di Sc. Fis., Mat. e Nat.*, **2,** 766 776, 1941.

Studi geologici e petrografici sul cristallino dei Monti Peloritani. *Bollettino del R. Ufficio geologico d'Italia*, **66,** Nota IV, 1–98, con carta geologica e tavole, 1942.

Sulle rocce eruttive del gruppo Ortles-Cevedale. *Rendiconti della R. Accademia d'Italia classe di Scienze Fis., Mat. e Nat.*, **3,** 289–304, 1942.

Studio petrografico di alcune argille montmorillonitiche pugliesi. *L'Industria Mineraria d'Italia e d'Oltremare*, **17,** 73–81, 1943.

La regola di orientazione dei cristalli di olivina nelle tettoniti. *Rendiconti della Società Mineralogica Italiana*, **3,** 41–42, 1946.

Appunti sopra l'origine dei graniti. *Ibid.*, **3,** 43–48, 1946.

L'origine dei reticoli a strati nell'alterazione dei minerali costituenti le rocce. *Periodico di Mineralogia*, **16,** 269–297, 1948.

La tettonica "a vortici" nei monti della Val di Sole. *Rendiconti del l'Accademia Nazionale dei Lincei, classe di Scienze Fis., Mat. e Nat.*, **5,** 60–67, 1948.

La linea di Peio nel massiccio dell'Ortler e le sue miloniti. *Acta Geologica Alpina*, **1,** 1–63, 1948.

Sull'alterabilita dei minerali delle rocce: *International Geol. Congress, Report of the 18th Session, Great Britain*, **1948,** Part 2, 5–8.

Studio del giacimento idrotermale di minerali argillosi di Capalbio (Orbetello): *Mem. dell'Acad. delle Scienze dell'Inst. di Bologna, classe Science Fisiche*, **5,** 51–65, 1947–48.

Studio di un interessante giacimento di riempimento di argille montmorillonitiche idrotermali (Vallortigara-Posina, Schio): *Ibid.*, **6,** 16, 1948–49.

Studio di un nuovo termine della serie illiti-idromiche in giacimento idrotermale e considerazioni sui passaggi miche-idromiche-montmorillonite. *Periodico di Mineralogia*, **18,** 12–31, 1949.

Origine dei giacimenti nel permiano superiore del Trentino e influenza del manganese sulla metallizzazione a galena argentifera. *Memorie del l'Istituto Geologico dell'Università di Padova*, **16,** 13, 1949.

A new type of illite-hydromica in a hydrothermal deposit. *Clay Minerals Bulletin*, **3,** 96–99, Galashiels, 1949.

Rapporti fra colate laviche e coperture di tufi in una zona meridionale del sistema dei profidi atesini (altopiano di Pinè). *Rendiconti dell 'Accademia Nazionale dei Lincei, classe di Scienze fis., mat. e nat.*, **6,** 563–569, 1949.

Le coltri di tufi del sistema profirico dell'altipiano meridionale di Pinè. *Ibid.*, **7,** 37–42, 1949.

Notizie sulla costituzione del complesso effusivo permiano del Trentino-Alto Adige. *Rendiconti della Società Mineralogica Italiana*, **6,** 48–53, 1949.

Studio petrografico e geologico dei giacimenti e delle argille montmorillonitiche idrotermali della Valle di Mogentale presso Posina (Vicenza). Memorie *dell 'Accademia delle Scienze dell 'Insituto di Bologna, classe di Scienze Fisiche,"* **7,** 1949–50, 31.

(con R. Pirani) I minerali del gruppo dell'Ortler. I. Actinolite e biotite di Val Madriccio. *Rendiconti dell'Accademia Nazionale dei Lincei, classe di Scienze fis., mat. e nat.*, **9,** 320–324, 1950.

Sulla rigenerazione di soluzioni metallifere e di magmi. *Ibid.*, **13,** 215–222, 1952.

Polymetamorphose und Tektonik in der Ortlergruppe. *Neues Jb. für Mineral., Monatshefte,"* 13–28, 1952.

Syntektonische und posttektonische magmatische Erscheinungen der Ortlergruppe in Beziehung zum alpinen Magmatismus. *Tschermaks mineral. und petrograph. Mitt.*, **3,** 93–114, 1953.

Sull'origine dei giacimenti e delle argille montmorillonitiche idrotermali della zona di Schio nell'Italia settentrinoale: *Comité International pour l'Etude des Argiles*, 149–161, 1952.

Über die Enstehung regenerierter Lagerstätten durch Magmatismus und tektonish-metamorphe Mobilisierung: *Neues Jb. Mineral. Mh.* 131–142, 1953.

Stoffmobilisierung und Stoffbewegungen bei der tektonischen Metamorphose: *Tschermaks mineral. und petrograph. Mitt.* 350–359, 1954.

Über die Verglimmerrung der Plagioklase in der tektonischen Metamorphose. *Tschermaks mineral. und petrograph. Mitt.*, 350–359, 1954.

Appunti sul metamorfismo: I—Mobilizzazione e movimenti di material nel metamorfismo tettonico. *Rendiconti della Società Mineralogica Italiana*, **10,** 3–18, 1954.

La Val di Peio e la Catena Vioz-Cevedale. *Acta Geologica Alpina*, **5,** 337, 1954.

Bermekungen über Metamorphose: Stoffmobilisierung und Stoffbewegungen bei der tektonischen Metamorphose. *Forstschr. der Mineral., Referate*, 56–57, 1953.

Analisi strutturali di rocce metamorfiche. VIII: compagini di parascisti di catazona (Val di Peio, Gruppo dell'Ortles). (in collaborazione con R. Pirani). *Periodico di Mineralogia* **23,** 125–145, 1954.

Noch einmal über die Regeneration von Lagerstätten und über die Stoffmobiliesierung. *Neues Jahr. für Mineral., Mon.*, 112–117, **1955**.

Attuali problemi sul metamorfismo, la tettonica e la metallogenesi nel critallino dei Peloritani. *Rend. Società Mineral. Ital.*, **11,** 38–45, 1955.

Un raro anfibolo manganesifero, dannemorite, nel giacimento ferrifero di Comasine in Val di Peio (gruppo dell'Ortles). (In collaborazione con R. Pirani). *Ibid.* **11,** 343, 1955.

Il metamorfismo tettonico e la granitizzazione del cristallino di Cima d'Asta. *Ibid.*, **11,** 343, 1955.

Sulla polingenesi delle rocce. *Atti dell'Accademia delle Scienze dell'Istituto di Bologna, classe Sc. Fis.*, **11,** 59–63, 1955.

Il problema delle facies metamorfiche e delle fasi petrogenetiche nella formazioni del cristallino antico alpino. *Rend. Società Mineral. Ital.*, **12,** 42–48, 1956.

Petrographische und petrotektonische Studien über die Entstehung der Magnesitlagerstätten des Zumpanels (Ortlergruppe) und über die geologische Geschichte der umgrenzenden Dolomitformationen. *Neues Jb. Mineral. Abh.*, 585–622, 1957.

Mineralogia e Cristallografia, 2nd. Ed. xii+880. Bologna, 1957.

Un contributo alla conoscenza dell'origine dei giacimenti di magnesite: giacimenti metasomatici di Zumpanel (Ortles). *Rend. Soc. Mineral. Italiana*, **13,** 71–106, 1957.

Le facies metamorfiche e il polimetamorfismo delle tettoniti alpine. *Ibid.* **13,** 107, 1957.

(con Guidicini) Nota preliminare di ricerche petrotettoniche sulle filladi feldispatizzate di Tenna (Trentino): *Ibid.*, **13,** 108–113, 1957.

Nuove osservazioni sulla serie basale della zona meridionale del sistema vulcanico atesino. *Ibid.*, **26,** 172–178, 1959.

Aufeinanderfolge der magmatischen Tatigkeiten im Grössten Permisch-Vulkanischen Schild der Alpen. *Geologischen Rundschau*, **48,** 99–111, Stuttgart, 1959.

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MEMORIAL OF HAROLD EUGENE BUCKLEY

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By the death, after a long illness, of Harold Eugene Buckley on 30th August, 1959, Britain lost one of its outstanding crystallographers. Born on 19th November, 1897, at Bolton, Lancashire, Buckley attended the local primary school and later Bolton Grammar School. During the First World War he served in France initially with the Grenadier Guards and later, on being commissioned, with the Loyal North Lancashire Regiment. On demobilization Buckley entered the Honours School of Chemistry in the University of Manchester, graduated in 1921 and took his master's degree the following year. At this time Sir Henry A. Miers was Vice-Chancellor of the University and it was due largely to his influence that Buckley was attracted to work in the field of crystallography. Buckley was appointed assistant to Miers in 1923 and although his earlier work was primarily concerned with the optical anomalies in a series of isomorphous double tartrates it was apparent that his main interests were in the growth, and the mechanism of growth, of crystals. On Miers' retirement in 1926 Buckley was appointed to a newly established Lectureship in crystallography, an appointment which although loosely associated with the department of physics allowed him the freedom of an independent unit within the Faculty of Science. His absorbing interest in crystal growth was thus able to develop unfettered along the lines which he himself planned. Buckley's attitude to crystallography was from the beginning highly individual and his independent approach, so characteristic of the man himself, was heightened by his conscious intention not to become a mere appendage of the Bragg school of *X*-ray crystallography.

In the thirties his work on the effects of ionic impurities on the growth of crystals was pursued with the greatest vigour and during this period he published in the Zeitschrift für Kristallographie some twenty papers which contain a wealth of detail on the experimental modification of crystal habit. The regularity of publication and the constancy with which his work appeared in the Zeitschrift were typical both of Buckley's zeal and of his fierce independence. His earlier work had been published in the Mineralogical Magazine but shortly, as the result of a disagreement with the editor, the late Dr. L. J. Spencer, he declared and carried out his intention in future to publish elsewhere. There is no doubt that by some of his colleagues Buckley's work was considered to be outmoded by the methods of *X*-ray crystallography. This attitude, however, served

Harold Eugene Buckley
1897–1959

nly to strengthen his resolve to pursue his investigations which at this ime were unique among British crystallographers.

It is unlikely that Buckley himself foresaw the magnitude of the in- erest in crystal growth which developed during the Second World War, r of the great increase in the needs of the telecommunications and lectronics industries for large clear crystals of substances with specific hysical properties. During the early stages in the development of this ew crystal-growing industry Buckley's experience and knowledge was nvaluable and the successful beginnings of commercially grown crystals n the United Kingdom were in no small measure a consequence of the eadiness with which he shared his knowledge with all who sought his dvice. The lack of a comprehensive account of crystal growth and dis- olution phenomena in English rendered Buckley's service the more aluable, but the awakened interest in both the experimental and theo- etical aspects of the subject emphasized the urgent need for a general extbook. In this field also it was Buckley who filled the breach and is book, Crystal Growth, was published in January, 1951. This work hich at the time of publication was the most complete and modern ccount of the theory and practice of crystal growth is now generally ccepted as the standard text in this subject.

Buckley was essentially a researcher but each year he gave a lecture ourse in crystallography. He was, however, unable to appreciate the xtent of the gulf between his knowledge and enthusiasm and that of the ndergraduate; consequently few students voluntarily attended his lasses and many went away without appreciating either the usefulness r the elegance of crystallographic methods and techniques. To the esearch student, and to his colleagues, Buckley presented a very differ- nt picture for he was always ready to give unlimited time and patience o those who brought their problems to him.

His university recognised Buckley's academic distinction firstly by his ppointment to a Senior Lectureship in 1937 and finally to a Readership n 1952. He was elected to Fellowship of the Mineralogical Society of merica in 1947. To those who knew him Buckley will be remembered ot only for the work he accomplished but also for the manner of its chievement based as it was on his fierce independence, great integrity nd complete singleness of purpose.

He leaves a widow and four sons, the two eldest of which he had the he pleasure of seeing graduate in his own university.

Bibliography

ome anomalous optical properties of freshly prepared mixed crystals of the Seignette salts: *Mineralog. Mag.*, **20,** 159–172 (1924).

he crystal structure of MgF_2: *Phil. Mag.*, **49** 945–951 (1925).

The crystal structures of the sulphides of mercury: *Mineralog. Mag.*, **20,** 382–392 (1925).

The anomalous optical properties of some new series of isomorphous double tartrates: *Mineralog Mag.*, **21,** 55–72 (1926).

The crystallization of potash alum and the effect of certain added impurities on its habit: *Zeit. Krist.*, **73,** 443–464 (1930).

The influence of RO_4 and related ions on the crystallization of sodium chlorate: *Zeit. Krist.*, **75,** 15–31 (1930)

Habit variation in crystals of Ba and Pb nitrates: *Zeit. Krist.*, **76,** 147–168 (1930).

Some examples of habit variation in crystals of $KMnO_4$: *Zeit. Krist.*, **78,** 412–421 (1931).

Further examples of habit variation in crystals of $KMnO_4$: *Zeit Krist.*, **80,** 238–254 (1931).

The influence of RO_4 and related ions in the habit of K_2SO_4 crystals: *Zeit. Krist.*, **81,** 157–168 (1932).

Variations of crystal habit in pure $KClO_3$: *Zeit. Krist.*, **82,** 31–37 (1932).

The growth of $KClO_3$ crystals in the presence of ionic impurities: *Zeit. Krist.*, **82,** 37–46 (1932).

A note on some excessively thin crystals of $KClO_3$: *Zeit. Krist.*, **82,** 47–49 (1932).

The effects of ionic impurities on the crystal habit of K_2CrO_4: *Zeit. Krist.*, **82,** 285–296 (1932).

Systematic habit-variation in $KClO_3$ crystals induced by dyes: *Zeit. Krist*, **85,** 58–73 (1933).

Examples of the "rutile in quartz" phenomenon in artificial crystals: *Zeit. Krist.*, **88,** 181–184 (1934).

The oriented inclusion of impurities in crystals: *Zeit. Krist.*, **88,** 248–255 (1934).

Molecular configuration and its relation to modification of crystal growth: *Zeit. Krist.*, **88,** 381–411 (1934).

On the mosaic structure in crystals: *Zeit. Krist.*, **88,** 221–241 (1934).

New evidence setting an upper limit to the dimensions of the mosaic block in crystals: *Zeit. Krist.*, **89,** 410–415 (1934).

Some new features in habit modification in $KClO_4$ crystals: *Zeit. Krist.*, **91,** 375–401 (1935).

Discussion regarding the mosaic: *Zeit. Krist.*, **93,** 161–163 (1936).

The regular association of $KMnO_4$ and $KClO_3$ crystals: *Zeit. Krist.*, **97,** 370–385 (1937).

Some problems connected with crystal growth: *Mem. Proc. Lit. Phil. Soc. Manchester* (1939).

Demonstration of optical interference figures: *Nature*, **143,** 801–802 (1939).

Morphological and dielectric studies of some crystals of the Rochelle salt type (with J. H. Thorp): *Acta Cryst.*, **2,** 333–337 (1949).

Habit modification in crystals as a result of the introduction of impurities during growth: *Discussions Faraday Soc.*, 243–254 (1949).

Crystal growth: New York, John Wiley, 571 pp.

Growth rates in EDT crystals (with A. H. Booth): *Nature*, **169,** 367 (1952).

Studies in the growth and habit modification of crystals: *Mem. Proc. Lit. Phil. Soc. Manchester*, 77–123 (1951).

The commoner surface features of SiC crystals; A note on difficulties associated with modern theories of crystal growth: *Deutsche Bunsen-Gesellschaft*, **56,** 275–282 (1952).

Growth rates of single crystals of ethylene diamine tartrate (with A. H. Booth): *Can. Journ. Chem.*, **33,** 1155–1161 (1955).

The effect of boric acid on the growth of ethylene diamine tartrate crystals (with A. H. Booth): *Can. Journ. Chem.*, **33,** 1162–1165 (1955).

Influence of dyes on supersaturation of salts, Part 1 (with R. K. Gupta): *Zeit. f. Phys. Chem.*, **204,** 165–174 (1955).

Influence of dyes on supersaturation of salts, Part 2 (with R. K. Gupta): *Zeit. f. Phys. Chem.*, **204,** 175–182 (1955).

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MEMORIAL OF BURNHAM STANDISH COLBURN

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Burnham Standish Colburn was born in Detroit, Michigan, December
1872, and died in his home in Asheville, North Carolina, December
, 1959. He was a descendant of Miles Standish, John Alden, Edward
oty, and Richard Warren, of the Mayflower, and had served at one
me as Governor General of the General Society of Mayflower De-
ndants. On November 21, 1900, he married Elizabeth G. Pierce, who
ed on January 12, 1959. He is survived by his brother, William B.
lburn, a son, Burnham Standish Colburn, Jr., three daughters, Eliza-
th (Mrs. E. Wayford Willmar), Evelyn (Mrs. Evelyn C. Thorn), and
ary Louise (Mrs. J. Frazier Glenn, Jr.), and several grandchildren.

Mr. Colburn received his B.S. in civil engineering at the University
Michigan in 1896. His first serious interest was in bridge building,
t it soon veered to banking and from 1911 to 1913 he was vice-presi-
nt of the People's State Bank in Detroit. Later he was Treasurer of the
more Estate Company, and from 1933 to 1953, President of the First
tional Bank and Trust Company of Asheville, North Carolina, where
had moved during the First World War. His interest in minerals ap-
rently dated from his childhood, his father having owned a large iron
ne. Soon after moving to Asheville, he became acquainted with Joseph
yde Pratt, State Geologist of North Carolina. He soon acquired a col-
tion of North Carolina minerals that was rated as the finest collection
its kind in the country, and a part of it was the Pratt collection, par-
ularly rich in gemstones from North Carolina. His interests centered
the southern Appalachian region, and the Spruce Pine area, with the
any dumps at abandoned mica mines and at the operating mines,
elded him many good specimens. Among these were specimens from
e old emerald mine near Little Switzerland, the rare pitchblende from
nland with its gaily colored alteration products, thin red garnets
closed in sheets of mica, and sheets of white mica with included
ystals of black mica and vice versa. These last were exhibited as trans-
rencies in the windows of his mineral room. Many other nearby locali-
es intrigued him immensely—Corundum Hill, Shooting Creek, Cowee
eek, Mason Mountain. Perhaps his greatest "field excursion" was his
opening, at great personal expense of both time and money, of the
mous old hiddenite mine near Stony Point.

Most of his collection was purchased in 1945 by friends and alumni of
e University of South Carolina and presented to the university for
rmanent exhibition in the Geology Department, as it was his wish
at the collection should be kept intact in a place where it would be

Burnham Standish Colburn
1872–1959

vailable to all. The specimens that he kept for himself at that time, to show to those who were interested, have now been donated by his family to form the nucleus of the Burnham S. Colburn Memorial Mineral Museum at 170 Cove Avenue, Asheville, sponsored by the Southern Appalachian Mineral Society, founded by Mr. Colburn.

Mr. Colburn became a member of the Mineralogical Society of America in 1930. In December 1936, in recognition of his lifelong interest in minerals and his great kindness and generosity to amateurs and professionals alike, he was elected a Fellow. He served as Vice-President for the year 1939.

The writer is one of many who enjoyed and benefited greatly by knowing this charming gentleman and his most hospitable family. No finer tribute could be written about him than to quote the statement recorded when the Southern Appalachian Mineral Society was formed (and probably written by Mr. Colburn himself)—"The objects of this society are to promote good fellowship and better acquaintance among its members, to add to the available information regarding mineral deposits of both commercial and museum value, to make such information readily accessible to the members, and to foster a free interchange of ideas."

In noting his passing, the Southern Appalachian Mineral Society recorded the following appreciation, "He welcomed friend and stranger to his home and to his office. He discussed minerals, he gave away specimens, he loaned books, he did all he could to foster knowledge and interest in the mineral world."

Austin Burton Edwards
1909–1960

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MEMORIAL OF AUSTIN BURTON EDWARDS

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Austin Burton Edwards Ph.D. (Lond.), D.Sc. (Melb.), D.I.C., I.A.I.M.M., was born in Melbourne in 1909 and educated at the Caul-eld Grammar School where he was captain and dux in 1926. In 1927 e commenced a science course at the University of Melbourne, became University half blue in football and graduated B.Sc. in 1930 with first ass honours in Geology. He was awarded the Howitt Natural History cholarship in Geology and later a Bartlett scholarship and then studied e geology and petrology of the Black Spur area, Healesville. This was e subject of the first of 128 published contributions to geological ience with which Dr. Edwards is identified either as sole or joint uthor. His second paper was a similar study of the Warburton area here the mountainous terrain gave full scope to his enthusiasm and hysical strength. These researches gained for him an 1851 Exhibition d enabled him, with the award of a free passage to England, to con-nue his studies at the Imperial College of Science in London. Here he ined his Colours in athletics during his course of study on the Tertiary lcanic rocks and dykes in South Gippsland and Central Victoria for hich he was awarded a Ph.D. in 1934.

He then chose to return to Australia and accepted an appointment as search officer in the Mineragraphic Section of C.S.I.R. which was then oused in, and closely identified with the Geological Department of the niversity of Melbourne. Thus commenced an association with Dr. F. L. illwell which became widely known through reports and publications d which endured, notwithstanding occasional attractive offers from verseas and elsewhere. There followed a series of studies of Australian es and ore deposits which was extended to the examination of mill roducts and mill tailings and eventually to smelter products such as attes, speisses and slags.

His first independent Mineragraphic task was the study of the occur-nce of Mn in iron ore of Iron Knob in South Australia. He extended is into a study of the iron ores of the Middleback Ranges. This was e first of a series of studies of iron ores which culminated in the recogni-on and discovery of the oolitic iron ores in the Northern Territory and onstance Range in Queensland.

At the same time he sustained a keen interest in petrological problems d completed at spare intervals various papers which he had initiated London, of which the more important were his studies on the Tertiary olcanic rocks of Central Victoria and the Differentiation of Dolerites of Tasmania. In 1937 he shared the David Syme Research Prize awarded by the Melbourne University with Professor R. D. Wright. He gained his Doctorate of Science in 1942.

On the retirement of Professor Skeats from the chair of Geology at the University of Melbourne in 1941 he was invited to lecture to the students on Mining Geology, pending the appointment of a lecturer in Economic Geology. These lectures, which continued till 1953, aroused his interest in Victorian coal and a series of papers on Wonthaggi and Victorian brown coals originated which eventually elevated him to a position of authority on brown coal and resulted in a request from the State Electricity Commission to act as geological consultant for them. He was given permission by C.S.I.R.O. to accede to the request and the fees for consulting were, by arrangement with C.S.I.R.O., allocated for the purchase of equipment for the Mineragraphic Section.

In 1946 a special post-graduate course was provided by the Geological Department of the University of Melbourne for eight Indian graduates. Dr. Edwards contributed to this course a series of lectures on mineragraphy and ore textures. These lectures provided the basis for his book entitled "Textures of Ore Minerals" which was published by the Australasian Institute of Mining and Metallurgy in 1947. This publication met with world wide success and a demand for it in mining schools and universities quickly exhausted the first edition. Dr. Edwards then prepared a new and enlarged edition which appeared in 1954 and has been followed by a reprinting in 1960. Ore minerals and their textures was the subject chosen by Dr. Edwards for the Clarke Memorial Lecture which he was invited to give to the Royal Society of New South Wales in 1952. The last honour received by him was the award of the Clarke Memorial Medal of the Royal Society of New South Wales in 1960.

In preparation for the Fifth Empire Mining and Metallurgical Congress in Australia in 1953 Dr. Edwards initiated a symposium on the Geology of Australian Ore Deposits. It was organised by a committee appointed by the Australasian Institute of Mining and Metallurgy with Dr. Edwards as chairman. The result was a volume comprising 135 articles contributed by the leading geologists in the Commonwealth which were edited by Dr. Edwards with the gaps filled in with his own editorial contributions. Consequent on this work Dr. Edwards served as assistant editor of the Proceedings of the Institute until his departure overseas.

In 1953 Dr. Edwards became Officer-in-Charge of the Mineragraphic Section when Dr. Stillwell reached the retiring age. The Section had moved out of the Geology building of the University in 1949 for new quarters in an adjacent building shared with the Commonwealth Department of External Affairs and the University Appointments Board. When the Commonwealth Department of Migrant Education vacated this building for larger premises Dr. Edwards was able to acquire further space to accommodate his increased staff and equipment.

Gradually over the years the scope of work undertaken by the Mineragraphic Section widened and in addition to the study of ores, igneous rocks and coal Dr. Edwards made contributions to sedimentary petrology, geochemistry, meteorites and geomorphology. The sedimentary petrology commenced with a study, jointly with G. Baker, of the Jurassic arkoses in Victoria and continued when the Mineragraphic Section was requested to examine the Mesozoic and Tertiary sediments of the Aure Trough, Purari Valley and the Wahgi Valley in Papua. His interest in geochemistry arose in the last few years from studies of the selenium content in sulphide deposits and the distribution of cadmium, manganese and iron in Broken Hill sphalerites. His descriptions of meteorites were a natural extension of his mineragraphic work, while his interest in geomorphology absorbed him during his vacations.

From 1953 onwards he was a member of the Council of the Australasian Institute of Mining and Metallurgy and, since 1949, a member of the Council of Caulfield Grammar School. His early interest in football was revived in later years when he accepted office as Vice-President of the University Football Club and coached the University Third football team for six years.

Honours that came to him from overseas included a Corresponding Fellowship of the Edinburgh Geological Society, nomination as Observer for 1958/61 for the Commission on Geochemistry of the International Union of Pure and Applied Chemistry, and election as a Foreign Member of the Mineralogical Society of India.

His overseas tour in 1960 to the mining fields in Europe and the centres of mineralogical research had been carefully planned even to the extent of acquiring some acquaintance with spoken Italian. He left with his wife on August 25th and travelled by air to Athens and after visiting some mines in Greece he moved on to Italy. His Italian tour was nearly completed when he collapsed and died in hospital in Rome. He was buried in the Protestant cemetery in Rome. He is survived by is wife, three daughters and a son.

With his death Australian geological science suffers the loss of an outstanding, unusually versatile and highly productive scientist whose clear thinking and rapid grasp of a problem was a constant help and guide to all associated with him. The loss of so brilliant and energetic a scholar at the height of his career is most keenly felt, both throughout Australia and overseas.

BIBLIOGRAPHY OF AUSTIN B. EDWARDS

Books

Textures of the Ore Minerals and their Significance, *Aus. Inst. Min. Met.* (1st Edit., 1947; 2nd edit., 1954), pp. 242, figs. 204.

Editor: Geology of Australian Ore Deposits, Pub. Fifth Empire Min. Met. Congr., Australia, 1953, Vol. I (Symposium: 135 articles, pp. 1300).

General Articles

Mineral Resources of Australia: in "*Australia—Its Resources and Development*" (Ed. G. L. Wood), McMillan, 1947, Ch. XIV, 177–212.

The Nature of Brown Coal: in *Brown Coal, Its Mining and Utilization* (Ed: Henderson), M.U.P., 1953 Ch. II, 19–61.

The Distribution of Brown Coal: *Ibid.*, Ch. III, 62–85.

The Composition of Victorian Brown Coals: in *Coal in Australia*, Pub. Fifth Empire Min. Met. Congr., Australia, 1953, Vol. **VI**, 727–753.

The Copper Deposits of Australia: *Proc. Aus. Inst. Min. Met. No.* **130** (1943), 105–171.

The Mineral Resources of the Western Pacific Islands: *Ibid.*, Nos. **146–147** (1947), 75–227 (in collaboration with M. F. Glaessner).

Laboratory Studies in the Search for Minerals; *Ibid.*, Nos. **156–157** (1950) 1–10.

The Ore Minerals and their Textures (Clarke Memorial Lecture), *Jour. Proc. Roy. Soc. N.S.W.* **85** (1952) 26–46.

The Present State of Knowledge and Theories of Ore Genesis, *Proc. Aus. Inst. Min. Met.* **177** (1956) 69–116.

Mineral Resources of Australia, in *Encyclopedia Americana* (new edition)

Mineragraphy

The Iron Ores of the Middleback Ranges, South Australia; *Proc. Aus. Inst. Min. Met.* No. **102** (1936) 155–207.

The Iron Ores of Yampi Sound, Western Australia; *Ibid.*, No. **110** (1938) 59–101 (in collaboration with F. Canavan).

Some Ilmenite Micro-structures and their Interpretation; *Ibid.*, No. **110** (1938) 39–58.

Some Observations on the Mineral Composition of the Mount Lyell Copper Ores, Tasmania and their Modes of Occurrence; *Ibid.*, No. **114** (1939) 61–110.

The Haultain Super-Panner, *Chem. Eng. Min. Rev.*, Sept. 1939.

Note on Lollingite and the Occurrence of Cobalt and Nickel in the Broken Hill Lode; *Proc. Aus. Inst. Min. Met.*, No. **114** (1939) 111–124 (in collaboration with F. L. Stillwell).

On the Mineral Composition of the Mount Oxide Copper Ore, Queensland; *Ibid.*, No. **118** (1940) 83–95.

A note on some Tantalum-Niobium Minerals from Western Australia; *Ibid.*, No. **120** (1940) 731–744.

Coated Gold from Cobar, N.S.W.; *Ibid.*, No. **121** (1941) 1–10 (in collaboration with F. L. Stillwell).

On the Occurrence of Platinum and Palladium at the Thomson River Copper Mine, Victoria, with a Note on the Optical Properties of Braggite; *Ibid.*, No. **125** (1942) 61–69. (in collaboration with J. S. Anderson and J. G. Hart).

The Mineral Association of Tennant Creek Gold Ores; *Ibid.*, No. **126** (1942) 139–144 (in collaboration with F. L. Stillwell).

The Mineragraphic Investigation of Mill Products of Lead-Zinc Ores, *Jour. C.S.I.R.*, **15** (1942) 161–174 (in collaboration with F. L. Stillwell).

The Chemical Composition of Leucoxene in Cainozoic Bauxite from Boolarra, Vic.: *Miner. Mag.*, **26,** (1942), 273–274.

The Composition of the Lead-Zinc Ores at Captain's Flat, N.S.W.; *Proc. Aus. Inst. Min. Met.*, No. **129** (1943) 23–40.

Mineral Composition of the Tin Ores of Renison Bell, Tasmania; *Ibid.*, No. **131–132** (1943) 173–186 (in collaboration with F. L. Stillwell).

Cobaltite in the Broken Hill Lode; *Ibid.*, No. 133 (1944) 21–27 (in collaboration with F. L. Stillwell).

The Mineral Composition of the Black Star Copper Orebody, Mount Isa, Queensland; *Ibid.*, No. **139** (1945) 149–159 (in collaboration with F. L. Stillwell).

An Occurrence of Sub-Microscopic Gold; *Ibid.*, No. **141** (1946) 31–46 (in collaboration with F. L. Stillwell).

Solid Solution of Tetrahedrite in Chalcopyrite and Bornite; *Ibid.*, Nos. **143–144** (1946) 141–155.

Ore and Granitization: Discussion; *Econ. Geol.*, **44** (1949) 234–241 (in collaboration with A. J. Gaskin).

Natural Ex-Solution Intergrowths of Magnetite and Hematite; *Amer. Mineral.*, **34** (1949) 759–761.

A Mineragraphic Study of Mattes and Speisses from Port Pirie Smelters; *Proc. Aus. Inst. Min. Met.*, Nos. **154–155** (1949) 29–38 (in collaboration with F. L. Stillwell).

The Composition of Some Lead Blast Furnace Slags from Port Pirie; *Ibid.*, Nos. **154–155** (1949) 41–67.

The Composition of Some Copper Slags from Port Kembla; *Ibid.*, Nos. **154–155** (1949) 69–84.

The Composition of Some Copper Mattes; *Ibid.*, Nos. **154–155** (1949), 85–102.

Jacobsite from the Tamworth District of New South Wales; *Mineral. Mag.*, **29** (1951) 338–341 (in collaboration with F. L. Stillwell).

Some Occurrences of Supergene Iron Sulphides in Relation to their Environments of Deposition; *Jour. Sed. Petr.*, **21** (1951) 34–46 (in collaboration with G. Baker).

Some Occurrences of Stannite in Australia; *Proc. Aus. Inst. Min. Met.*, Nos. **160**-**161** (1951) 5–59.

Mineralogy of Middleback Iron Ores; in *Geology of Australian Ore Deposits*, Fifth Empire Min. Met. Congr., 464–472 (1953).

Mount Oxide Copper Mine; *Ibid.*, 391–395 (1953).

Conrad Lodes; *Ibid.*, pp. 950–954 (1953) (in collaboration with M. Wade).

Supergene Ore at the Girofla Mine, Mungana; *Proc. Aus. Inst. Min. Met.*, No. **170** (1953) 5–17 (in collaboration with E. Broadhurst).

The Mineral Composition of the Yerranderie Silver-Lead Ores; *Ibid.*, No. **170** (1953) 73–101.

The Composition of the Lead-Zinc Ores at Captain's Flat, N.S.W., II; *Ibid.*, No. **170** (1953) 101–131 (in collaboration with G. Baker).

The Oxidation of Stannite Ore at the Sardine Tin Mine; *Ibid.*, No. **172** (1954) 65–79 (in collaboration with G. Baker).

anded Hematite Quartzites from the Middleback Range: South Australia; *Bull. Geol. Surv. South. Aus.* No. **33** (1954) App. II, 206–210.

ranium Minerals from Mount Painter; *Bull. Geol. Surv. South. Aus.* No. **30** (1954) 94–114 (in collaboration with F. L. Stillwell).

The Mineral Composition of Ore from the Hill 50 Gold Mine; *Proc. Aus. Inst. Min. Met.* No. **174** (1955) 33–42.

he Composition of the Peko Copper Orebody, Tennant Creek; *Ibid.*, No. **175** (1955) 55–82.

Hypogene Goethite at Peko Mine, N.T.: Australia; *Am. Mineral.*, **41** (1956) 657–660.

Metamorphism and Metasomatism at King Island Scheelite Mine; *Jour. Geol. Soc. Aus.*, **3** (1956) 55–98 (in collaboration with G. Baker and K. J. Callow).

Uralite Dolerite Dykes in Relation to the Broken Hill Lode; *Proc. Aus. Inst. Min. Met.* No. **178** (1956) 213–232 (in collaboration with F. L. Stillwell).

Mineralization at Aberfoyle Tin Mine, Rossarden, Tasmania; *Ibid.*, No. **181** (1957) 93–145 (in collaboration with R. J. P. Lyon).

Microscopical Examination of Gold Smelting Products; *Indian Mining Jour.*, **5** (1957) 317–319 (Special Issue: Symposium on Mineral Beneficiation etc., Jamshedpur, 1957).

The Mineral Composition of the Maude and Yellow Girl Ore, Glen Wills, Victoria; *F. L. Stillwell Anniversary Volume, Aus. I.M.M.*, (1958) 105–132.

Oolitic Iron Formations in Northern Australia; *Geol. Rundschau*, **47** (2): (1958) 668–682—Australienheft.

Discussion: Sedimentary Structures in the Metamorphic Rocks and Ore-Bodies, Broken Hill, N.S.W. by M. A. Condon; *Proc. Aus. Inst. Min. Met.*, No. **189** (1959) 65–77.

Contrasting Textures in the Silver-Lead-Zinc Ores of the Magnet Mine, Tasmania: *Neues Jahrb. f. Min., Special Paul Ramdohr Festband*, **94** (1960) 298–318.

The Roper River Oolitic Ironstone Formations (in collaboration with G. W. Cochrane); *Mineragraphic Investigations Technical Paper* No. **1**, C.S.I.R.O., Australia (1960).

Geochemical

The Selenium Content of Some Australian Sulphide Deposits; *Proc. Aus. Inst. Min. Met.* No. **172** (1954) 31–63 (in collaboration with G. C. Carlos).

Cadmium in the Broken Hill Lode; *Ibid.*, No. **176** (1905) 71–96.

Manganese and Iron in Broken Hill Sphalerites; *Ibid.*, No. **180** (1956) 97–117.

Meteorites

The Bond Springs Stony Meteorite; *Mem. Nat. Mus. Melb.*, No. **12** (1941) 49–58 (in collaboration with G. Baker).

The Tawallah Valley Meteorite; *Rec. Aus. Mus.*, **21** (1941) 1–8 (in collaboration with T. Hodge Smith).

The Pakenham Meteorite; *Proc. Roy. Soc. Vic.*, **54** (1942) 7–16 (in collaboration with G. Baker).

A Note on the Micro Texture of the Arltunga Meteorite; *Rec. Aus. Mus.* **21** (1943) 154–155.

The Koraleigh Stony Meteorite; *Mem. Nat. Mus. Melb.* No. **13** (1943) 157–160 (in collaboration with G. Baker).

The Cranbourne Meteorites; *Ibid.*, No. **14** (1944) 23–35 (in collaboration with G. Baker).

The Moorumbunna Meteorite; *Trans. Roy. Soc. S. Aus.*, **70** (1946) 348–353.

The Wedderburn Meteoritic Iron; *Proc. Roy. Soc. Vic.*, **64** (1953) 73–76.

The Lismore Meteoritic Iron, Victoria; *Ibid.*, **72** (1960) 93–94.

Coal and Coal Petrology

Geology of the Wonthaggi Coalfield; *Proc. Aus. Inst. Min. Met.* No. **134** (1944) 1–54 (in collaboration with G. Baker and J. Knight).

The Composition of Victorian Brown Coals; *Ibid.*, No. **140** (1945) 205–280.

Clarain and Durain in Greta Coal; *Ibid.*, No. **145** (1947) 38–45 (in collaboration with B. Langham).

Coal Types in the Yallourn and Latrobe Brown Coal Seams; *Ibid.*, Nos. **146–147** (1947) 23–69.

me Effects of Folding on the Moisture Content of Brown Coal; *Ibid.*, Nos. **150–151** (1948) 101–112.

al Types in the Maddingley Brown Coal Seam, Bacchus Marsh; *Ibid.*, Nos. **150–151** (1948) 113–115.

ank and Type of Some Australian Coals; *Fuel*, **29** (1950) 125–133.

sain in Some Victorian Brown Coals; *Proc. Aus. Inst. Min. Met.* No. **170** (1953) 47–71.

SEDIMENTARY PETROLOGY

rassic Arkose in Southern Victoria; *Proc. Roy. Soc. Vic.* **55** (1943) 195–228 (in collaboration with G. Baker)

e Glauconitic Sandstone of the Tertiary of East Gippsland; *Ibid.*, **57** (1945) 153–166.

e Petrology of the Miocene Sediments of the Aure Trough, Papua; *Ibid.*, **60** (1950) 123–148.

e Petrology of the Cretaceous Greywackes of the Purari Valley, Papua; *Ibid.*, **60** (1950) 163–171.

esozoic and Tertiary Sediments from the Wahgi Valley, New Guinea; *Ibid.*, **64** (1953) 93–112 (in collaboration with M. F. Glaessner).

IGNEOUS AND METAMORPHIC PETROLOGY

e Geology and Petrology of the Black Spur Area, Healesville; *Proc. Roy. Soc. Vic.*, **44** (1932) 49–76.

e Geology and Petrology of the Warburton Area, Victoria; *Ibid.*, **44** (1932) 168–181.

the Dacite-Granodiorite Contact Relations in the Warburton Area; *Ibid.*, **44** (1932) 182–194.

tiary Dykes and Volcanic Necks of South Gippsland, Victoria; *Ibid.*, **47** (1934) 112–132.

ree Olivine Basalt-Trachyte Associations and Some Theories of Petrogenesis; *Ibid.*, **48** (1935) 13–26.

the Occurrence of Almandine Garnets in Some Devonian Igneous Rocks of Victoria; *Ibid.*, **49** (1936) 40–50.

the Occurrence of Quartz-Tourmaline Nodules in the Granite of Clear Creek, near Everton; *Ibid.*, **49** (1936) 11–17.

he Igneous Rocks of North-Eastern Benambra; *Ibid.*, **50** (1937) 69–96 (in collaboration with J. G. Easton).

uartz Diorite Magma in Eastern Victoria; *Ibid.*, **50** (1937) 97–109.

he Tertiary Volcanic Rocks of Central Victoria; *Quart. Jour. Geol. Soc. Lond.*, **94** (1938) 243–320.

trology of the Older Volcanic Rocks of Victoria; *Proc. Roy. Soc. Vic.*, **51** (1938) 73–98.

ertiary Lavas from the Kerguelen Archipelago, *B.A.N.Z. Antarctic Research Exped.*, 1929–31, Reports Ser. A, Vol. **II,** Pt. 5, (1938) 72–99.

he Formation of Iddingsite; *Am. Mineral.*, **23** (1938) 277–281.

holeiite Basalts from Cape Gosselin, Western Australia; *Jour. Roy. Soc. W.A.*, **22** (1935–36) 19–23.

ertiary Tholeiite Magma in Western Australia; *Ibid.*, **24** (1937–38) 1–12.

ranites of King George Land and Adelie Land," *Australasian Antarctic Exped., Sci. Repts.* Ser. A, Vol. **IV,** Pt. 3 (1940) (in collaboration with H. S. Summers).

he Cainozoic Volcanic Rocks of the Gisborne District, Victoria; *Proc. Roy. Soc. Vic.*, **52** (1940) 281–311 (in collaboration with W. Crawford).

me Cambrian Basalts from the East Kimberley, W.A.; *Jour. Roy. Soc. W.A.*, **26** (1939–40) 77–94 (in collaboration with E. de C. Clarke).

he Crinanite Laccolith of Circular Head, Tasmania; *Proc. Roy. Soc. Vic.*, **53** (1941) 403–415.

Some Basalts from the North Kimberley, W.A.; *Jour. Roy. Soc. W.A.*, **27** (1940) 79–93.

Differentiation of the Dolerites of Tasmania; *Jour. Geol.*, **50** (1942) 451–480; 579–610.

Contact Phenomena in the Morang Hills, Victoria; *Proc. Roy. Soc. Vic.*, 56 (1944) 19–34 (in collaboration with G. Baker).

Alkali Hybrid Rocks of Port Cygnet, Tasmania; *Ibid.*, **59** (1947) 81–115.

The Petrology of the Cainozoic Basaltic Rocks of Tasmania; *Ibid.*, 62 (1950) 97–120.

Petrology of the Principal Talc Deposits in South Australia; *Bull. Geol. Surv., S. Aus.* No. **26** (1952) (in collaboration with F. L. Stillwell).

Crinanite-Picrite Intrusions in the Nebo District of New South Wales; *Proc. Roy. Soc. Vic.*, **65** (1953) 9–29.

Scapolitization in the Cloncurry District of North-Western Queensland; *Jour. Geol. Soc. Aust.*, **1** (1954) 1–33 (in collaboration with G. Baker).

Manganiferous Dolomites and Related Rocks from the Middleback Range, South Australia; *Bull. Geol. Surv. S. Aus.* No. **33** (1954) App. III, 211–213.

Petrological Study of Rocks from the Middleback Range and Environs; *Ibid.*, No. **33** (1954) App. IV, 214–230.

Petrology of the Bauxites of Tasmania; C.S.I.R.O., Melb., 1955, pp. 45.

The Rhyolite-Dacite-Granodiorite Association of the Dandenong Ranges; *Proc. Roy. Soc. Vic.*, **68** (1956) 111–149.

Amphibolites from the Broken Hill District; *Jour. Geol. Soc. Aus.*, **5** (1958) 1–32.

GEOMORPHOLOGY

The Age and Physiographical Relationships of Some Cainozoic Basalts in Central and Eastern Tasmania; *Pap. Proc. Roy. Soc. Tas.*, (1938) 169–199.

A Note on the Physiography of the Woori Yallock Basin; *Proc. Roy. Soc. Vic.*, **52** (1940) 336–341.

On a Remnant of a Stripped Peneplain of Palaeozoic Age at Mount Sedgwick in Western Tasmania; *Pap. Proc. Roy. Soc. Tas.*, (1941) 19–22.

The North-West Coast of Tasmania; *Proc. Roy. Soc. Vic.*, **53** (1941) 233–260.

Storm-Wave Platforms; *Jour. Geomorph.*, **4** (1941) 223–236.

The San Remo Peninsula; *Proc. Roy. Soc. Vic.*, **54** (1942) 59–74.

A Dome-like Structure in the Jurassic Rocks of South Gippsland; *Ibid.*, **54** (1942) 224–228.

The Geology of Philip Island; *Ibid.*, **57** (1945) 1–16.

Wave Action in Shore Platform Formation; *Geol. Mag.*, **88** (1951) 41–49.

Wave-cut Platforms at Yampi Sound, W.A.; *Jour. Roy. Soc. W.A.*, **41** (1958) 17–21.

THE AMERICAN MINERALOGIST, VOL. 46, MARCH-APRIL, 1961

MEMORIAL OF JOHN TIPTON LONSDALE

E. Wm. Heinrich, *Mineralogy Department, University of Michigan.*

John T. Lonsdale died suddenly and unexpectedly of a heart attack October 5, 1960 at 1:30 A.M. at his home in Austin, Texas. To those ho never knew him this can be read as a simple statement of fact. or those of us who knew him and thus loved him no amount of repeti- on will ever convince us that it is completely true.

Who can portray a man by parading the sequence of his life events? hn Tipton Lonsdale, born November 8, 1895 at Dale, Iowa was the dest son of John Dye Lonsdale and Eva Mary Lonsdale, nee Connor. ter an elementary school education at Dale and high school training Guthrie Center, he was awarded his B.A. (1917) and M.S. (1921) the University of Iowa. His studies were interrupted from 1917 to 19 when he served as First Lieutenant in the Army of the United ates during which time he was cited for bravery by both the United ates and Italian governments.

Upon his return from war he married Edna Gertrude Von Arnam on igust 13, 1921. Mrs. Lonsdale recalls a long personal debate in deciding ether to resume with geology or to continue as a professional military an; he had received a commission as a first lieutenant in the post-war my. Geology won and he began his professional career as Assistant ofessor of Geology at the University of Virginia and Assistant Geolo- st with the Geological Survey of Virginia (1921–1924). The Degree of octor of Philosophy in Geology was awarded him by the University of rginia in 1924.

At the University of Oklahoma he served as Assistant Professor of ology in 1924 and continued as field geologist for the Oklahoma ological Survey in the summers of 1924 and 1925. His career with e Texas Bureau of Economic Geology began in 1925 when he became sociate geologist, rising to geologist in 1927. From 1928 to 1935 he as Professor of Geology and chairman of the geology department at xas A. and M. College, a combination of posts he also held from 1935 1942 at Iowa State College. While at College Station, Texas, he was so geologist for the Missouri Pacific Railroad. He returned to military rvice from 1942 to 1945 as Lieutenant Colonel and Colonel, General aff Corps and continued as a colonel in the U. S. Army Reserve until 53.

In 1945 he was recalled to become Director of the Texas Bureau of onomic Geology and Professor of Geology with graduate rank, posi- ons he held at the time of his death. To the complex duties of this manding situations he brought devotion, energy, intelligence and good dgement, efforts that rapidly placed the Bureau into the foremost

John Tipton Lonsdale
1895–1960

nks of state geological surveys. His own geological interests centered ound petrology, ground water, and economic geology. Special mention ould be made of his initiation of a comprehensive investigation of the neral resources of the State of Texas and of his painstaking and ginal studies of the igneous rocks of the Big Bend National Park, Terlingua-Solitario region and the Balcones fault region. His geo- ical interests were catholic, his strivings devoted, his achievements lid.

The scientific and honorary societies which he faithfully served were ny: Sigma Gamma Epsilon, Sigma Xi, Society of Economic Geolo- ts, Geological Society of America (fellow), Mineralogical Society of nerica (fellow), American Association for the Advancement of Science, nerican Association of Petroleum Geologists, American Institute of ning, Metallurgical and Petroleum Engineers and Society of Eco- mic Paleontologists and Mineralogists. Numerous committees of many these and other organizations obtained his services, and in 1959 he vice-president of the Association of American State Geologists and president-elect of this organization at the time of his death.

His manifold interests were also manifest in his non-professional ivities. He was active in the Austin Rotary Club, collected guns and ed to hunt on a deer lease held with a group of friends for over 15 rs. Humble in demeanor, modest in word, and true in thought he a devoted friend and a delightful companion. In recognition of his vices to his country, his ashes have been interred at Arlington National metery.

As these words are written at the desk in his study in the house that him was home, in view of his books, guns and other belongings that, upon his passing have reverted to inanimate matter, it is clear that outline is but that. It remains for the memories of his friends to plete the picture. John Lonsdale is survived by a great sense of loss, his wife, a sister and a brother and, though he had no sons, we, his dents, also remain.

BIBLIOGRAPHY

ne effects of heat on the properties of minerals: *Am. Mineral.*, 141–147, August 1923.

t-Cincinnatian granites of northeastern piedmont Virginia: *Jour. Geol.*, **34,** 159–166, 1926.

h C. N. Gould) Geology of Texas County, Oklahoma: *Okla. Geol. Surv. Bull.* **37,** 62 pp., 1926.

h C. N. Gould) Geology of Beaver County, Oklahoma: *Okla. Geol. Surv. Bull.* **38,** 72 pp., 1926.

iedmont Virginia magmatic complex: *Am. Jour. Sci., 5th ser.*, **11,** 505–513, 1926.

er and soda niter from Brewster County, Texas: *Am. Mineral.*, **11,** 189–190, 1926.

occurrence of caliche in Oklahoma (abs.): *Iowa Acad. Sci., Proc.*, **1925,** 32, 357, 1926.

logy of the gold-pyrite belt of the northeastern piedmont, Virginia: *Va. Geol. Surv. Bull.* **30,** 110, 1927.

(with Adkins, W. S.) Euhedral orthoclase crystals from Sierra Blanca, Texas: *Am. Mineral.*, **12,** 256–259, 1927.

The Florence meteorite of Williamson County, Texas: *Am. Mineral.*, **12,** 398–404, 1927.

Igneous rocks of the Balcones fault region of Texas: *Texas Univ. Bull.* **2744,** 178, 1927.

(with Crawford, David J.) Pseudo-igneous rock and baked shale from the burning of lignite, Freestone County, Texas: *Texas Univ. Bull.* **2801,** 147–158, 1928.

Analcite from Brewster County, Texas: *Am. Mineral.*, **13,** 449–450, 1928.

Diphrite and associated contact minerals from the Franklin Mountains of Texas: *Am. Mineral.*, **14,** 26–32, 1929.

An underground placer cinnabar deposit (Brewster County, Tex.): *Econ. Geol.*, **24,** 626–631, 1929.

Euhedral magnesite crystals from Winkler County, Tex.: *Am. Mineral.*, **15,** 238–239, 1930.

(with Metz, M. S., and Halbouty, Michel Thomas) The petrographic characters of some Eocene sands from southwest Texas: *Jour. Sed. Petrol.*, **1,** 73–81, 1931.

Underground water resources of Atascosa and Frio Counties, Tex.: *U. S. Dept. Interior Press Memo.* **66110,** 9, 1932.

(with Day, James R.) Ground-water resources of Webb County, Tex.: *U. S. Dept. Interior Press Memo.* **68861,** 9, 1933.

Geology and ground-water resources of Atascosa and Frio Counties, Tex.: *U. S. Geol. Surv. Water-Supply Paper* **676,** 90, 1935.

Investigation of underground water resources (abs.): *Pan-Am. Geologist*, **65,** 1936.

Investigation of underground water resources of Texas (abs.): *Iowa Acad. Sci. Proc.* **1936,** 249, 1937.

(with Day, James R.) Geology and ground-water resources of Webb County, Tex.: *U. S. Geol. Surv. Water-Supply Paper* **778,** v, 104, 1937.

The Plantersville meteorite, Grimes County, Tex.: *Am. Mineral.*, **22,** 877–888, 1937.

Igneous rocks of the Terlingua-Solitario region, Texas: *Geol. Soc. America Bull.*, **51,** 1539–1636, 1940.

Origin of analcite in igneous rocks of the Terlingua District, Texas (abs.): *Iowa Acad. Sci. Proc. 1939*, **46,** 252, 1940.

The Peña Blanca Spring meteorite, Brewster County, Texas *Am. Mineral.* **32,** 354–364, 1947.

(with Dickson, Kathryn O.) Analcime suite of igneous rocks, Brewster County, Texas (abs.): *Geol. Soc. Am. Bull.*, **59,** 1337, 1948.

(with Maxwell, Ross Allan) Petrology of Big Bend National Park, Texas (abs.): *Geol. Soc. Am. Bull.*, **60,** 1906, 1949.

(with Barbeck, A. H.) Mineral and geological resources of Red and Arkansas basins in Texas: Minutes Fifth Meeting AWRB Inter-Agency Committee, Appendix H, pp. 1–3, 1951.

Texas minerals: Manufacturers Record, 109–110, November 1951.

Preservation of wall samples and cores: Shale Shaker, March 1952.

Brown iron ores of Texas: Preprint, Amer. Inst. Mining Eng., September 1952.

(with Dickson, Kathryn O.) Native lead, Presidio County, Texas (abs.): *Bull. Geol. Soc. of Amer.*, **63,** 1276, 1952.

(with F. F. Uetzeband) Texas chapters in annual editions of Minerals Yearbook, U. S. Bur. of Mines, 1953–1957.

(with Ross, A. Maxwell, John A. Wilson and Roy T. Hazzard) Big Bend National Park, Guidebook 1955 Spring Field trip, West Texas Geol. Soc., 1955.

(with Joseph M. Perkins) Mineral Resources of the Texas Coastal Plain, *Mineral Res. Circ.* **38,** *Texas Bur. Econ. Geol.*, 1955.

(with John W. Dietrick) Mineral Resources of Colorado River Development Association area, *Univ. of Texas Bur. Econ. Geol. Rept. Inv.* **37,** 1958.

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MEMORIAL OF GRAHAM STEWART MacKENZIE

W. E. Hale, *Geology Department, University of New Brunswick.*

The sudden passing of Graham Stewart MacKenzie on May 5, 1960 ocked and saddened his many friends who sincerely sympathize with s wife Alice, his two sons Blake and Ross, his father, four brothers and vo sisters.

Graham MacKenzie was born in Toronto in 1905 but spent most of s early years in Winnipeg. He graduated from the University of Mani- ba with the degree of Bachelor of Science in 1929. He attended the niversity of Toronto and received from there the degrees of Master of rts and Doctor of Philosophy in 1930 and 1934 respectively. His Ph.D. esis entitled "Some Post-Cambrian Mineral Deposits of the St. wrence Basin," involved a combination of his major interests: eco- mic geology, mineralogy and chemistry.

From 1928 until the completion of his academic training at Toronto 1934, he worked in the provinces of Manitoba, Ontario and Quebec. e gained from E. L. Bruce, J. M. Thompson and B. T. Denis excellent d interesting field training and experience which was to become so luable to him during subsequent years as geologist and teacher. From ese early travels and associations he also developed a collection of necdotes and stories of the "bush" which never failed to interest and tertain his students and friends.

Graduating during the depression, Graham's qualities, experience and aining served him well and he joined the staff of the Quebec Bureau Mines where he worked under the direction of the late J. A. Dresser r whom he frequently expressed great respect and admiration.

In 1935 Alice Ross, originally of Bridgewater, N. S. became Mrs. raham MacKenzie and during the next 25 years she graciously and uietly combined her natural social talents with those of her husband a manner which made their home a friendly, informal and intellec- ually stimulating haven for students, professors, professional colleagues nd the many friends who came to know and respect them through the ears.

Graham joined the staff of the University of New Brunswick in 1937 nd became Professor and Head of the Department of Geology in 1945. he Department grew rapidly in quality and numbers of students under is leadership, and during his last years, a program of post-graduate aining and research was developed which gained for the department nd the university, reputation and respect in many quarters. In 1957 udents and former students organized a dinner and presentation to emonstrate in a simple but serious fashion their thanks for the many 'extra' kindnesses they had received from Graham and Alice MacKenzie.

He served his adopted province with enthusiasm and distinction in the field as well as in the classroom and laboratory. He worked for the federal and provincial surveys, unravelling some of the problems of Appalachian Geology in New Brunswick and always gave freely of his time to encourage, advise and assist those, either professional or amateur, interested in rocks and minerals.

The discovery of the large base metal deposits in Northern New Brunswick is rightly credited to an early program of exploration which Graham MacKenzie devised and directed. Although the material aspects of his life did not vary greatly as a result of his endeavors, his modest pride in achievement was a more important compensation.

It was however to his students that Graham devoted the bulk of his energies and his genuine interest and warm sympathy endeared him to faltering freshmen and aggressive graduates alike. His office door was always open and students of all departments found in "Doc" MacKenzie a willing, sincere, respected and capable confidant. His unselfish service to many worthy organizations and university committees reflected the respect and unassuming authority which he commanded from within and outside academic circles.

In part as recognition of his contribution of the discovery of the base metal deposits in the Bathurst-Newcastle camp, the University of New Brunswick conferred on him an honorary Doctorate in Science in 1953 and Mount Allison University granted him posthumously an honorary Doctorate in Law in May, 1960. He was a Fellow of the Royal Society of Canada, a Fellow of the Geological Association of Canada, a Member of the Canadian Institute of Mining and Metallurgy, a Fellow of the Mineralogical Society of America, a Member of the Mineralogical Association of Canada and the Canadian Institute of International Affairs. He also served the Canadian Advisory Committee on Research in the Geological Sciences.

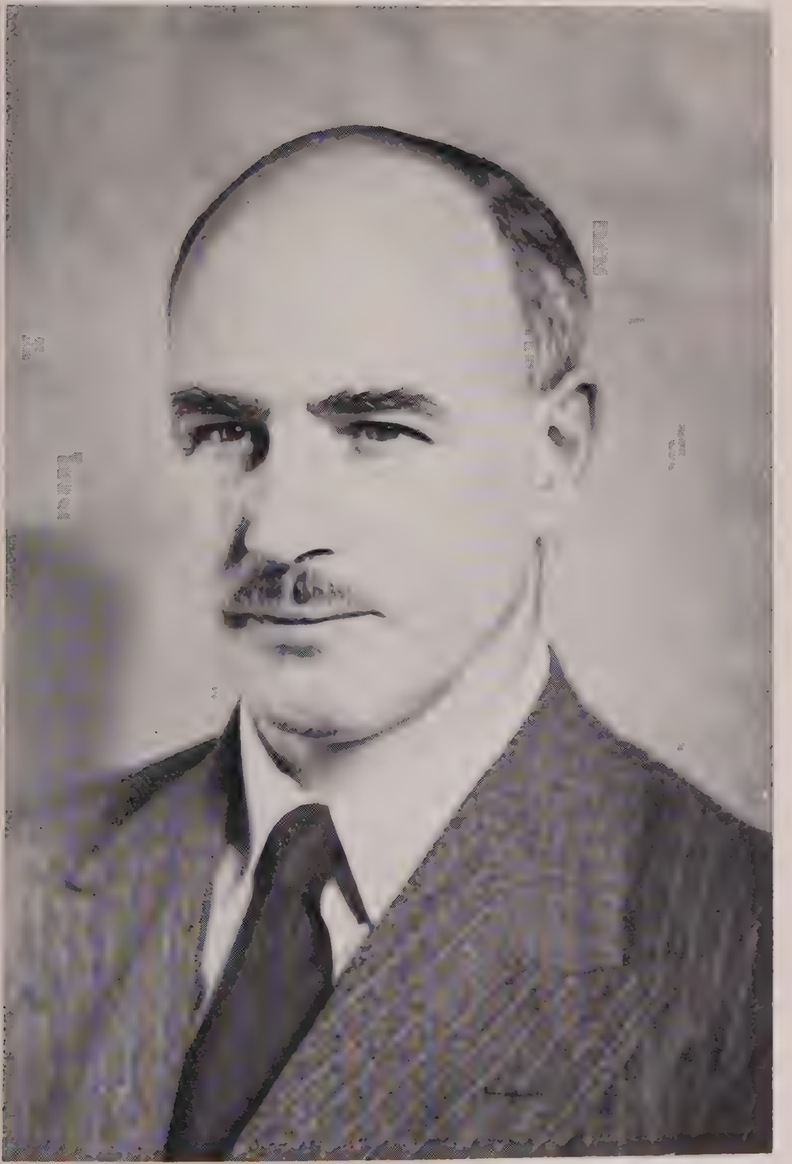
Graham MacKenzie's warm friendliness, good humour, keen intelligence and modest mien will be remembered and missed especially by his students and colleagues within the much larger number of his friends and acquaintances.

SELECTED LIST OF PUBLICATIONS BY GRAHAM STEWART MACKENZIE

(with D. R. Derry) Geology of the Manitoba Ontario Boundary Line (12th Base Line to Latitude 54), *Annual Report, Ont. Dept. of Mines*, 1931, **Part II, 40.**

Pusticamica Lake Map Area, Abitibi District: *Que. Bur. Mines, Ann. Rep. for 1934*, **Part C,** 1935, 45–64.

Madeleine Lake Gold Discovery: *Que. Bur. Mines, Ann. Rept. for 1934*, **Part A,** 1935, 125–132.



Graham Stewart MacKenzie
1905–1960

Field Report on the Currie Township Map Area: *Que. Bur. Mines, Prelim. Rep.* **105,** 1935.

Currie Map Area, Abitibi District: *Que. Bur. Mines, Ann. Rept. for 1935,* **Part B,** 1936, 81–108.

Mining Properties of the Chibougamau-Opemisca Region: *Que. Bur. Mines, Prelim. Rep.* **111,** 1937.

The Arntfield Area, Abitibi County: *Que. Bur. Mines, Prelim. Rep.* **122-B,** 1938.

The Halliwell Mine Map Area: *Que. Bur. Mines, Prelim. Rep.* **131,** 1939.

Fortune Lake and Wasa Lake Map Areas, Dasserat and Beauchastel Townships: *Que. Bur. Mines, Geol. Rep.* **5,** 1940.

The St. Stephen Area, Charlotte County, Paper **40-6,** *N. B. Dept. of Lands and Mines,* 1940.

Halliwell Mine Map Area, Beauchastel township: *Que. Bur. Mines, Geol. Rep.* **7,** 1941.

The Mt. Champlain Map Area: *Report of the N. B. Dept. of Lands and Mines,* **1941.**

Lead, Zinc and Silver Prospect at Reserve Brook, Queens County, N. B.: Paper **42-1,** *N. B. Dept. of Lands & Mines,* 1942.

The Bathurst Iron Mine Report & Map: *N. B. Dept. of Lands and Mines,* **1943.**

The Mt. Pleasant Map Area, N. B. Prelim. Map: *N. B. Dept. Lands and Mines,* **1943.**

The Reserve Brook Lead-Zinc Deposit, New Brunswick: *Acadian Naturalist,* **1943.**

Clones Coal, Queens County, *Paper* **44-2,** *N. B. Dept. Lands and Mines,* 1944.

The Vernon Copper Mine: *Paper* **45-1,** *N. B. Dept. of Lands and Mines,* 1945.

The Crock Point, Macnataquac Dam-Sites: *N. B. Resources Development Board,* **1945.**

(with F. J. Alcock) The Sussex Map-Area, *N. B.*: *Geol. Surv. Canada, Map* **845A,** 1946.

Bathurst Iron Mine, New Brunswick: *Paper* **49-2,** *N. B. Dept. Lands and Mines,* 1949.

The Hampstead Map-Area, New Brunswick: *Geol. Surv. Canada, Paper* **51-19,** 1951.

The Westfield Map-Area, New Brunswick: *Geol. Surv. Canada Paper* **51-15,** 1951.

(with F. J. Alcock) Geology of the St. Stephen Area, Charlotte Co., N. B.: *Map* **1096A,** *Geol. Survey of Canada,* 1960.

THE AMERICAN MINERALOGIST, VOL. 46, MARCH-APRIL, 1961

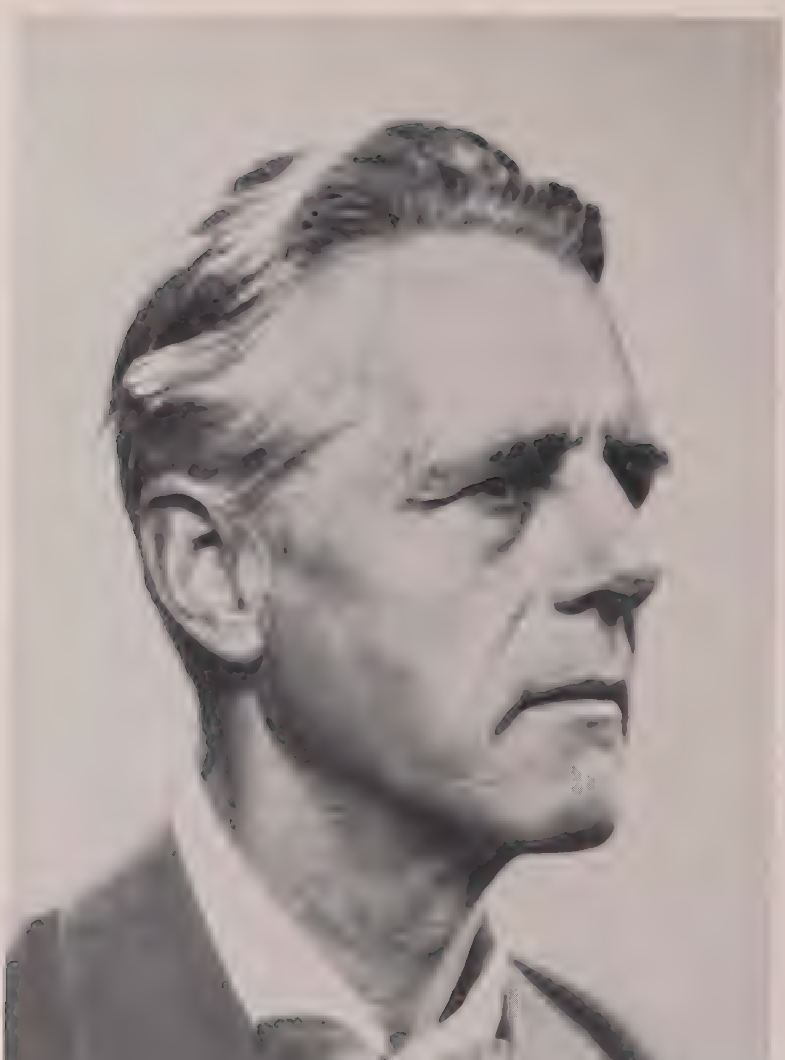
PRESENTATION OF THE ROEBLING MEDAL TO TOM. F. W. BARTH

GEORGE TUNELL, *University of California, Los Angeles, California.*

Mr. President, Fellows and Members of the Mineralogical Society of America, and Guests:

In 1936 the Council of the Mineralogical Society of America directed that a gold medal be designed in honor of Colonel Washington Augustus Roebling, a noted civil engineer who had long been interested in mineralogy and who had served as Vice-President of the Society in 1924. The Council further indicated that this medal was to be awarded for important contributions to the mineralogical sciences both in the United States and in other countries.

The award this year will be the nineteenth and the first to a Norwegian mineralogist. The person selected by the Council to be the recipient, Prof. Tom. F. W. Barth, was born in Norway in the town of Molde in 1899. A few months later he was taken to Bosekop, a small settlement near the North Cape, where he lived until he entered school at Trondhjem. In 1919 he entered the Royal Frederic's University in Oslo, and there became a student of Prof. W. C. Brøgger, whose investigations of the igneous rocks of the Oslo province are classical. As early as 1894 Brøgger had concluded that within a series of congenetic igneous rock types, the differentiation was determined by the laws of crystallization. From 1924 to 1927 Barth came under the stimulating influence of Prof. V. M. Goldschmidt and participated in some of Prof. Goldschmidt's researches on crystal structures and the geochemical distribution of the elements. In 1927 he received the degree of Doctor of Philosophy from Oslo University. In 1927 and 1928 he was an Assistant Professor in the Technische Hochschule in Berlin and in 1928 and 1929 he held a similar position in the University of Leipzig. From 1929 until 1936 he was a member of the scientific staff of the Geophysical Laboratory of the Carnegie Institution of Washington. In 1936 he returned to Norway to become a Professor in Oslo University and Director of the Mineralogisk Institutt, and he held these positions through the Second World War. For a time he was confined in a prison camp by the German army along with many other members of the University faculty, but his scientific research was continued in spite of many handicaps. In 1946 Dr. Barth joined the faculty of the University of Chicago as Professor of Geochemistry, but after three years he returned once more to his native land to assume the post of Director of the Mineralogisk-Geologisk Museum and to resume the position of Professor in Oslo University. Since then he has left Norway only briefly.



Tom. F. W. Barth

Dr. Barth's researches have covered a wide range of subjects in mineralogy, petrology, and geochemistry. His x-ray study of perovskite and dysanalyte in 1925 showed that their atomic arrangement is a simple one of approximate cubic symmetry, but actually of lower symmetry. A few years later in collaboration with Dr. E. W. Posnjak he determined the atomic arrangement of ilmenite. Its structure is similar to that of hematite, but its symmetry was proved to be lower because an atom of titanium takes the place of every other iron atom in the hematite unit cell. A very comprehensive investigation of the structures of the spinel group of minerals and related artificial compounds was carried out by Dr. Barth and Dr. Posnjak in the course of which they discovered that, while some of these minerals have the classical type of structure described by W. H. Bragg and by S. Nishikawa for spinel and magnetite, on the other hand magnesioferrite and several related artificial compounds have a remarkably different structure. In magnesioferrite 8 of the trivalent iron ions occupy one set of equivalent positions and the other 8 trivalent iron ions together with the 8 divalent magnesium ions are statistically distributed over one set of equivalent positions in a disordered manner. Previous to the work of Barth and Posnjak it had not been recognized that in a pure chemical compound atoms or ions of two or more chemical elements might be distributed statistically in a disordered way over one set of equivalent positions. An x-ray investigation by Dr. Barth of the sodalite family of minerals in which variate atom equi-points are also present, cleared up confusion of long standing concerning the chemical formulas of noselite and haüyne and gave an accurate picture of the atomic arrangements in these minerals.

I have mentioned some of the x-ray researches of Prof. Barth first, because I am more cognizant of his crystallographic contributions than of his field investigations. From his student days, however, he has spent much time mapping the igneous and metamorphic rocks in numerous Norwegian and American areas and working out their petrogenetic elations. As a result of his studies of the plutonic rocks in the Oslo Province, Barth concluded that the development of the principal plutonic ock series of this Province was conditioned by the development of various mineral reaction series, particularly by the two reaction series of he feldspars.

He has also carried out extensive investigations of the granitic and neissic rocks of southern Norway near Kristiansand and determined he approximate temperatures at which they were formed by the use f the distribution ratio of soda in coexisting feldspars as a temperature ndicator. Barth's general conclusion is that the pre-Cambrian granites f southern Norway were mostly formed by anatexis, although there are three granitic bodies in this region that exhibit sharp contacts and that crystallized at temperatures about 150° C. higher than those at which the encasing gneisses were metamorphosed; these three granitic masses he believes were emplaced as hot crystalline bodies. In a petrographic investigation of basalt lavas from many parts of the world Barth has shown that the various types have originated mainly by crystal fractionation, and he further demonstrated that in almost all basaltic lavas only one pyroxene is present, the composition of which shifted progressively from diopsidic to clinohypersthenic during the process of differentiation.

While Dr. Barth was a member of the staff of the Geophysical Laboratory, he became interested in the work of Dr. A. L. Day, Dr. E. T. Allen, and Dr. H. E. Merwin on the hot springs, geysers, and fumeroles of the Yellowstone National Park. With the encouragement and support of Dr. Day, who was at that time the Director of the Geophysical Laboratory, he undertook a comprehensive investigation of the volcanic activity, hot springs, and geysers in Iceland which is reported in a magnificently illustrated monograph constituting Carnegie Institution of Washington Publication Number 587. In the conclusion of this work Barth states that: "The volcanic hot springs of Iceland form an evolutionary series from acid to alkaline (pH 2→9). The acid springs are rich in 'volcanic' gases hydrogen, hydrogen sulfide, and carbon dioxide and contain very small amounts of nitrogen. In the course of evolution, hydrogen sulfide and hydrogen are consumed by wallrock alterations and by oxidation. Thus springs rich in carbon dioxide are formed. Eventually the carbon dioxide is consumed also, and springs emerging at great distances from the volcanic centers, for instance in Tertiary basalt, usually contain more than 99 per cent nitrogen plus argon. Such springs have clear water and show alkaline reaction." Barth's findings for the Icelandic hot springs are thus in very good agreement with those of Day, Allen, and Merwin for the hot springs of Yellowstone National Park.

I have attempted to touch upon but a few of Prof. Barth's scientific contributions, which are embodied in a long series of scientific papers, several monographs, and a well balanced treatise on petrology. His achievements have been recognized by the University of Copenhagen, which awarded him an honorary doctoral degree in 1950, and by the University of Nancy, which awarded him an honorary doctoral degree in 1960. In 1959, on his sixtieth birthday, the Norwegian government conferred upon Prof. Barth the Royal Order of St. Olav, the highest honor that it awards for civilian achievement. He is a fellow of the following royal academies: Norske Videnskaps Akademi, Oslo, Norway;

Kungliga Fysiogafiska Sällskapet, Lund, Sweden; Kongelige Videnskabs-Selskab, Copenhagen, Denmark; Royal Society of Edinburgh, Scotland. He is an Honorary Member of the Geological Society of London, of the Geological Society of Belgium, and of the Geological Society of France, a Corresponding Member of the Geological Society of America and of the Geological Society of Finland, a Member of the Geological Society of Norway, of the Geological Society of Sweden, of the Geological Society of Denmark, of the Deutsche Mineralogische Gesellschaft, of the Geochemical Commission of the International Union of Chemistry (of which he was also President in 1957–1960), and of the Geochemical Society (of which he was also President in 1960). And finally he is a Fellow of the Indian Mineralogical Society and of the Mineralogical Society of America.

Mr. President: It is a great pleasure as well as a valued privilege to introduce my old friend and former colleague, Prof. Barth, for the award of the Roebling Medal.

PRESENTATION OF THE ROEBLING MEDAL BY PRESIDENT MURDOCH

Thomas Frederick Weybye Barth, geologist and mineralogist, distinguished for your investigations in a wide range of subjects, notably the x-ray determination of unusual crystal structures, the course of differentiation in basaltic lavas, and demonstration of the reaction series in the alkali feldspars: it is my pleasure as President of the Mineralogical Society of America to present to you the Roebling Medal in recognition of these achievements.

THE AMERICAN MINERALOGIST, VOL. 46, MARCH–APRIL, 1961

ACCEPTANCE OF THE ROEBLING MEDAL

T. F. W. BARTH.

President Murdoch, Dr. Tunell, Fellows, Members, Guests:

In the first book of Confucious which was written about 2500 years ago, there is a passage saying: "Isn't it a pleasure to have friends who come from far away to visit you." This year I have been visited by thoughts and by letters from friends who live far away.

When I received the letter from our president, Dr. Murdoch, stating that you had selected me as the recipient of the Roebling Medal, it was a message from the other side of the globe giving me a pleasant shock. After some reconsideration it occurred to me that it was not, perhaps, so much myself, as it was my teachers and friends in many lands whom the Council of the Society wanted to honor; for this, I thank you from a full heart.

It was easy for me to become a mineralogist. As a student I was fortunate to be associated with V. M. Goldschmidt in his most active period of life. I was fascinated by his genius and drank avidly from his cornucopia of new ideas in mineralogy and crystal chemistry.

Through him I was introduced to the best in German science; I lectured for two years in the department of Professor K. H. Scheumann whose wide interests and artistic abilities made a deep impression on me.

Still in my twenties, I was fortunate to receive an International Rockefeller grant (a rare dispensation at that time) to study at Harvard with R. A. Daly, Esper Larsen, Charles Palache and others. The kindness of these men and their inspired teaching kindled in me an enthusiasm and devotion to mineralogy that can never die.

To top my share of luck, I was soon accepted on the staff of the Geophysical Laboratoy in Washington, D. C.—another great opportunity for me. I want to mention Dr. A. L. Day, the director of the Laboratory, E. S. Shepherd, and certainly N. L. Bowen, whose original experiments and original ideas -as we all know were revolutionary in the development of our field of science. Many years later Bowen also brought me back to America; this time to Chicago for a few years.

And last, but not least, I should mention Dr. H. S. Washington. He was dear to my heart, and I cherish his memory most affectionately. He was a perfect gentleman, cultured, handsome. with kind, clear brown eyes, and an impressive beard. He was the finest of scholars, and he taught me, not only science and research, but also ethics, wisdom and natural philosophy.

Finally, I have had to do something on my own account. For better or for worse, I have spent most of my time in Norway. I have enjoyed field work and mapped large areas of Precambrian rocks. Compelled by my own observations I have become a SOAK, in spite of my respect for V. M. Goldschmidt, my admiration for Bowen, and my warm feelings for Esper Larsen.

In conjunction with this work, I developed the two-feldspar geologic thermometer. It may need modification and perhaps the details are more complicated than pictured by me. But the principle is right. And it has been great fun. Dr. Washington said to me: "In order to do research it is necessary to have a particularly brilliant mind, or a very high intelligence. To be able to do good research is a state of mind." I hope that through him I have acquired that state of mind.

Mr. President, I cannot find adequate words. I am grateful for the Medal, and I want to express my sincere thanks to the Mineralogical Society of America. But only to these old teachers and friends of mine, goes the honor.

THE AMERICAN MINERALOGIST, VOL. 46, MARCH-APRIL, 1961

PRESENTATION OF THE 1960 MINERALOGICAL SOCIETY OF AMERICA AWARD TO DONALD L. GRAF

JULIAN R. GOLDSMITH, *University of Chicago, Chicago, Illinois.*

Mr. President, Fellows, and Members of the Mineralogical Society of America, and Guests:

Donald L. Graf is this year's recipient of the Mineralogical Society of America Award. In a presentation of this sort it is usually stated that the proceedings give a great deal of pleasure to the presentor. This must, in some people, be due to a pleasurable sensation produced by the inverse audiovisual experience, in others to a vicarious association with the person being honored, and in still others to a generally false feeling of equality or even superiority induced by their unique task and elevated attitude before an unparticipating and seated audience. Then there are those whose expressed feeling of pleasure is a downright lie.

How can I say that what I am doing is a pleasure? I am playing the part usually reserved for staid, mature, and what many of the younger people would even call "elderly" duffers. The Mineralogical Society of America Award has been called the young man's award. In 1955 I found myself in the seat Don now occupies. Can one find pleasure in having aged so in 5 short years?

Donald Graf received his undergraduate degree in Geologic Engineering at the Colorado School of Mines, and his M.A. and Ph.D. at Columbia University. His only place of business has been with the Illinois Geological Survery, since December, 1948. The 1960 Award is given to him for significant research on the calcium-magnesium carbonates. I shall not dwell on details of his work, but will assume that those really interested know them. I would rather quote to you directly from Oscar Hammerstein II, who said the following about Richard Rodgers:

"His melodies are clean and well defined. His scores are carefully built, logically allied to the stories and characters they describe. No overgrown forests or weed-clogged meadows of music here, but neat rows of tenderly grown flowers on well-kept lawns. Pseudo-artists and dilettante critics might interpret these comments as disparaging. The impulsive creator of overgrown forests of music might seem a more powerful and more important and more rugged fellow. Speaking for myself, I am bored with undisciplined talent. The intertwining vines and aimless vegetation that spring from careless genius are of little use to a world which suffers from obscurity, and not too much clarity. Life is so short that no musician has the right to expect any appreciable number of people to devote any appreciable part of their listening lives to the wild free notes that dribble from his talented but casual fingers. A large

Donald F. Geat

number of musical compositions, a large number of grand operas and light operas, are too long, too carelessly put together, and fail for this reason. They are not above the heads of the public. They are just not worthy of the public because the creative artist involved has been too self-indulgent actually to finish off his job."

Don not only has shown the ability of finishing off a piece of research very well indeed, but he has shown the growth and desire necessary to continue to attack new problems with new approaches. This Award is intended for a man whose accomplishments represent points on a rising curve, and I am sure that Don is a long way from an inflection.

Mr. President, I have the privilege of presenting to you, Dr. Donald L. Graf, as the 10th recipient of the Mineralogical Society of America Award.

Presentation of the Award by President Murdoch

Donald Lee Graf, able and industrious worker through whose researches the complexities of the carbonate rocks are being untangled: it is my pleasure as President of the Mineralogical Society of America, to present to you the Society's Award for 1960, with the firm expectation that you will continue successfully to investigate this and other mineralogical problems.

THE AMERICAN MINERALOGIST, VOL. 46, MARCH-APRIL, 1961

ACCEPTANCE OF THE MINERALOGICAL SOCIETY OF AMERICA AWARD

Donald L. Graf, *Illinois State Geological Survey, Urbana, Illinois.*

I suppose we all wonder at times whether our activity in a particular corner of science is of any interest or use to anyone else. When no one comments on an error in a published paper, this can be more discourgaing than losing the argument that should have developed. Recognition from one's society, such as you have just bestowed upon me, is therefore particularly heartwarming as evidence of one's relationship to the larger scientific community. I appreciate very much the encouragement that you have given, and can only hope that in the years ahead it will prove to have been warranted.

It has been my good fortune to be employed by an organization, the Illinois State Geological Survey, that has generously supported a program in my case divorced from routine tasks. I owe a great deal to having had the chance to work closely with Julian Goldsmith and W. F. Bradley. And, above all, I am indebted to John Haff who sought to explain to us at the Colorado School of Mines the nature of proof and the difference between quality and quantity, and who was responsible for sending me to work under Professor Kerr at Columbia University. Professor Haff once spent an hour explaining to us in vivid detail that we really knew nothing about anything. We were by then past masters at physical chemistry and integral calculus, and it was generally agreed that the professor was badly in error.

Dr. Goldsmith has suggested to you that I am interested in carbonates. This is true. More broadly, I am interested in applying physical and chemical techniques to understanding the mechanisms of equilibrium and nonequilibrium processes in sedimentary environments. A number of us have recently made a modest start toward a basin-wide study of the solids and liquids contained in the Pleistocene evaporite sequence of the Great Salt Lake Desert. The definitive constants in such studies, of course, must frequently be obtained at experimental temperatures and pressures well removed from those which exist in sediments and sedimentary rocks.

Rather than go on at length about research plans, however, I should like to comment on the professional atmosphere within mineralogy and geochemistry since World War II. In my experience it has been a time of remarkable generosity and openness, and of cooperative relationships springing up between widely separated people of diverse interests. The situation is surely the exact opposite of that which in the 1870's led Professor Leidy to conclude that, because of the activities of Marsh and Cope, vertebrate paleontology was no longer a fit occupation for gentlemen. I think, the absence of animosities of any consequence results not from the greater perfection of human beings in 1950 and 1960, but simply from the fact that earth scientists are seated at a mammoth banquet table and know and accept that fact. There are more worthwhile things to be done than any of us can hope to handle, even with the aid of 50 graduate students. The recent bursts of activity in the fields of solid state physics, isotopic chemistry, and marine sedimentation, for example, have opened whole new areas of activity for mineralogists and geochemists, and we are on the verge of extraterrestrial sampling.

Most of us come to the banquet table with a discouragingly small number of concepts and research techniques at our command, in comparison with the spectrum revealed, for example, by a single issue of *Chemical Abstracts*. This frustrating situation is for the most part inevitable, but earth scientists, nevertheless, have been making a determined effort to achieve greater versatility. There has been a general tendency to plunge into new and enticing fields without exhaustive preparation but with a determination to subject the results of these excursions to severe scrutiny. After all, if Professor Haff was right about the general state of knowledge, there is less reason to be afraid of another man's field. This bursting of previously sacred frontiers allows a geoscientist these days to contemplate adventures in astronomy, chemistry, physics, mathematics, and zoology, in addition to geology. Professor Urey has pretty well covered the list. One is soon brought face to face with the realization that in addition to the old limitations of time, money, equipment, and personal intelligence, there is a highly variable personal limit to the rate at which one can learn new techniques and concepts and still remain happy and productive.

It is not only because of the fine personal relationships and the stimulating variety of problems at hand that I have enjoyed the past ten years spent in science. At the risk of seeming trite, I must emphasize that the long range viewpoint, the dedication to excellence, and the relatively objective standards of evaluation in science are qualities that I find missing in much of the world around me. These qualities were present to a very considerable degree in the Iowa farming villages where I grew up, and they still are.—If the members of the society are surprised at the comparison, I can only suggest that the astonishment in Iowa would probably be comparable.

Thank you very much.

THE AMERICAN MINERALOGIST, VOL. 46, MARCH–APRIL, 1961

PROCEEDINGS OF THE FORTY-FIRST ANNUAL MEETING OF THE MINERALOGICAL SOCIETY OF AMERICA AT DENVER, COLORADO

GEORGE SWITZER, *Secretary.*

The forty-first meeting of the Society was held on October 31–November 2, 1960, at the Denver Hilton Hotel, Denver, Colorado. The scientific sessions were integrated with those of the Geological Society of America and other affiliated Societies. A total of 43 scientific sessions were held. Of these two were devoted to mineralogy, one to crystallography, one to petrology, and four to geochemistry, at which 114 papers were presented.

The annual luncheon of the Society on November 1 was attended by 200 fellows, members and guests. Following the luncheon the eighteenth presentation of the Roebling Medal was made to T. F. W. Barth and the tenth presentation of the Mineralogical Society of America Award was made to Donald L. Graf.

On the afternoon of November 1, the Society was addressed by Retiring President Joseph Murdoch on the subject *Crestmore – Past and Present.* The annual business meeting was held on the morning of November 2, at which reports were given by the Secretary, Treasurer, and Editor. An announcement of an International Mineralogical Association meeting to be held in Washington, D. C., in April 1962 was made by International Mineralogical Association President, D. J. Fisher.

ACTION OF THE 1960 COUNCIL

The 1960 Council of the Society met on the afternoon and evening of October 30 and the morning of October 31 for a total of seven hours.

Mineralogical Abstracts. The International Mineralogical Association Abstracts Commission met in Copenhagen in August 1960 to discuss the ultimate goal of having an international abstracts journal. The most promising plan envisages the extension of *Mineralogical Abstracts*, presently owned jointly by the Mineralogical Society of America and the Mineralogical Society of Great Britain. To this end the following note was approved by the Councils of both societies, to be circularized by the Abstracts Commission to all known national societies or associations:

> During the Copenhagen meeting of the International Mineralogical Association the new Commission on Abstracts discussed the organization of a comprehensive journal of mineralogical abstracts.
>
> The most promising plan envisages the extension of *Mineralogical Abstracts*, at present owned jointly by the Mineralogical Society of Great Britain and the Mineralogical Society of America. With the approval of the Councils of both these societies, the Commission is sending this letter to all known national mineralogical societies in an effort to obtain their co-operation.
>
> I. *Mineralogical Abstracts* could be readily enlarged if more abstracts covering different countries were available. Regional or national societies can secure for all their members a 50% reduction in the cost by agreeing to contribute free of charge Engilsh abstracts comprising a comprehensive coverage of papers appearing in their region; they need undertake no other responsibility. Members of such societies would pay $4.50 (U. S.) for personal annual subscription to *Mineralogical Abstracts* compared with the full subscription rate of $9.00. National mineralogical societies in Canada, Japan, Norway and Switzerland are already partaking in this scheme.
>
> II. The question of a wider ownership of *Mineralogical Abstracts* is being considered but the British and American societies feel that it woud be premature to extend

ownership prior to 1963. They feel that more experience of the present financial arrangement would be essential to devise an equitable scheme. Both the Brith and American societies put up appreciable capital sums in order to start *Mineralogical Abstracts* (as from vol. 14); moreover they have agreed to stand losses that *Mineralogical Abstracts* might incur. Members of the British society pay an annual subscription of the equivalent of $3.00 for *Mineralogical Abstracts* and this is included in their subscription to the *Mineralogical Magazine*, i.e. they cannot contract out of buying *Mineralogical Abstracts*. Members of the American society can purchase *Mineralogical Abstracts* for $3.00 which may be included in their dues at their discretion. The subscriptions appropriate to wider ownership would depend considerably on the number of participating countries.

Awards. The Council voted that in 1961 the Roebling Medal be awarded to Paul Ramdohr, and the Mineralogical Society of America Award be presented to Joseph V. Smith.

Election of Fellows. In 1960 there were 49 candidates for Fellow placed on the ballot. Following past procedures, the Secretary had printed a booklet giving biography and bibliography of each candidate. This required a 79 page booklet, and even though it was typed and produced by photo offset, the cost of preparing the booklet was nearly $700. The Secretary suggested that in the future a method patterned after that used by the Geological Society of America and the Society of Economic Geologist be followed: The following form was suggested and approved by the Council:

To the Fellows of the Society:

> The Secretary sends you herewith vita on the candidates on the enclosed ballot for election as Fellows. The candidates have been approved by the Council on recommendation by the Nominating Committee for Fellows. The complete bibliography of any candidate may be obtained by writing to the Secretary not later than August 1, 1961.

The vita on each candidate will consist of a brief biography, number of publications and general nature of major publications, and names of sponsors. This new short form will be followed in presenting candidates for election in 1961.

Financial Advisory Committee. The report of the Committee was accepted. The Council voted to drop the matter, raised the preceding year, of a commercial audit of the Society's books.

Membership List Publication. The Council voted that the Executive Committee bring to the 1961 Council recommendations for publishing the membership list separately by photo offset from adressograph plates.

Mistake in by-Laws. In November 1951 the Council recommended the following amendment in Article II, Section 3 of the By-Laws, and voted that it be placed on the ballot in 1952 for approval by the membership:

> Fellows and members who have reached the age of 70 years, or have reached the official retirement age of the institution in which they have been serving, and have paid annual dues for 30 years, shall be exempt from further payment of dues but retain all rights and privileges. (From Proceedings, *Am. Mineral.*, **37**, 276, 1952.)

This above item appeared on the ballot distributed to the membership in 1952, but the result of the vote does not appear in the Proceedings of the following year or in subsequent years, nor in the Secretary's reports to the Council in subsequent years.

There has been no authority for any change in the wording of Article II, Section 3 of the By-Laws between the time that it appeared on the ballot in 1952 and in the revision of the By-Laws approved by the Council in 1957 and printed in 1958 (*Am. Mineral.*, **43**, 611–614). Therefore, this section in the 1958 printing of the By-Laws is incorrect.

The Council feels that the simplest way to correct the mistake is to place Article II, Section 3 of the By-Laws, as originally worded and recommended by the Council in 1951, and (probably) voted by the membership in 1952, on the 1961 ballot to be reaffirmed and thereby annul the error in the wording of this section in the revised By-Laws approved in November 1958. The Council, therefore, voted that the above proposed change be placed on the 1961 ballot for vote by the membership.

Use of Mailing List. The Council voted that the present practice be continued of selling the MSA mailing list to concerns such as book publishers, if by so doing a service would be rendered to the membership, and that the charge to be made for the use of the list be left to the discretion of the Treasurer.

Storage of Back Issues of the American Mineralogist. The Council was informed by the Editor that the stock of most of the back issues of *The American Mineralogist*, now stored at the University of Michigan, must be moved within a year. The Council voted that the back issues be moved to Silver Spring, Maryland, and that storage, sales, and distribution of back issues be taken over by the Treasurer's office.

Funds for Travel to Annual Meeting. The Secretary pointed out that the 1946 Council authorized travel expenses of five cents per mile for the Secretary, Treasurer, and Editor to attend the annual meeting of the society. The Council reaffirmed this past Council action.

General Interest Articles in The American Mineralogist. Richard H. Jahns reported that he has compiled a list of 22 famous mineral localities, and is ready to inaugurate a series of articles of professional quality on famous mineral localities. The Council reiterated its approval of the project, and voted that Dr. Jahns and the Editor be empowered to use their best judgment in the selection of articles.

ACTION BY THE 1961 COUNCIL

Editor of The American Mineralogist. The Council appointed Lewis S. Ramsdell Editor of *The American Mineralogist* for the year 1961.

Co-Editor of The American Mineralogist. The Editor requested that the Council appoint a Co-Editor, to begin work immediately, and to take over full editorship of the journal at the end of 1961. The immediate duties of the Co-Editor would be to receive and evaluate all manuscripts, send them to referees, and to be responsible for all book reviews. These two functions represent about one-third of the editorial work load. The Council appointed E. W. Heinrich Co-Editor of *The American Mineralogist* for the year 1961.

American Geological Institute. The Council voted that the Mineralogical Society of America contribute no more than $500 to the American Geological Institute in 1961, at the will of the Executive Committee.

International Mineralogical Association. The Council voted that $150.00 be paid during 1961 as the Society's dues to the *International Mineralogical Association.*

Ten Year Index of The American Mineralogist. The Council voted that Joseph Murdoch be appointed Chief Indexer, to begin preparation of the next 10-year index of *The American Mineralogist*, for volumes 41–50.

International Mineralogical Association Meeting in Washington, D. C., in Spring 1962. The date of the meeting was set for April 18–20, 1962, with field excursions before and after the meeting. The Council voted that Alvin Van Valkenburg be appointed General Chairman of the local committee.

Archivist. The Society has never had an Archivist, and there is increasing danger as years pass that records relating to the Society's founding and early history will become lost. The Council voted that George T. Faust be appointed Archivist, and that he be requested to begin the task of assembling all pertinent papers and information.

Committee Appointments. President Osborn made the following committee appointments, which were approved by the Council:

1961 COMMITTEES OF THE MINERALOGICAL SOCIETY OF AMERICA

Nominating Committees for Fellows

R. Roy, *Chairman*	1960–62
E. N. Cameron	1959–61
J. L. Kulp	1959–61
C. F. Park, Jr.	1960–62
W. S. MacKenzie	1961–63
R. S. Cannon	1961–63

Roebling Medal Committee

R. M. Garrels, *Chairman*
C. A. Anderson
H. L. James
H. Kuno
C. E. Tilley
G. Tunell

Program Committee

H. Winchell
J. W. Peoples, alternate

Nominating Committee for Officers

C. L. Christ, *Chairman*
J. C. Griffiths
H. H. Hess
A. L. Howland
H. F. McMurdie
R. G. Coleman

Auditing Committee

A. Van Valkenburg, *Chairman*
M. L. Lindberg
G. L. Davis

Nomenclature Committee

J. V. Smith, *Chairman*	1959–61
G. Tunell	1959–61
G. T. Faust	1960–62
A. Pabst	1960–62
M. Fleischer	1961–63
C. Frondel	1961–63

MSA Award Committee

E. W. Nuffield, *Chairman*
W. F. Bradley
I. H. Milne
K. J. Murata
H. F. W. Taylor
J. B. Thompson

Financial Advisory Committee

E. P. Henderson, *Chairman*	1959–61
A. Montgomery	1960–62
W. T. Pecora	1961–63

Endowment Committee

C. B. Slawson

Advisory Committee on Russian Translations to the American Geological Institute

Earl Ingerson, *Chairman*

Representatives

American Geological Institute

Board of Directors:

R. M. Grogan	1960–61
J. F. Schairer	1961–62

Government Relations Committee:

P. F. Kerr	1959–61

International Mineralogical Association

Representative:
A. Pabst
Members of Commissions:
Abstracts—H. Winchell
Data—G. T. Faust
New Minerals and New Mineral Names—D. McConnell
Museums—G. Switzer
Teaching of Mineralogy—C. S. Hurlbut, Jr.

American Association for the Advancement of Science

P. F. Kerr
E. E. Wahlstrom

National Research Council

W. F. Bradley	1960–63

Nominations for Officers for 1962. The following slate was proposed by the Nominating Committee and approved by the Council:

President: Ian Campbell, California Division of Mines, San Francisco, Calif.
Vice-President: Cornelius S. Hurlbut, Jr., Harvard University, Cambridge, Mass.
Secretary: George Switzer, U. S. National Museum, Washington, D. C.
Treasurer: Marjorie Hooker, U. S. Geological Survey, Washington, D. C.
Councilors: (1962–64, two to be elected)

R. B. Ferguson, University of Manitoba, Winnipeg, Canada
Harold L. James, U. S. Geological Survey, Menlo Park, Calif.
Francis J. Turner, University of California, Berkeley, Calif.
Hatten S. Yoder, Jr., Geophysical Laboratory, Washington, D. C.

REPORT OF THE SECRETARY

To the Council of the Mineralogical Society of America

Election of Officers and Fellows

Nine hundred and forty-nine ballots were cast in the election of officers, 131 by Fellows and 818 by Members. The officers elected to serve in 1961 are:

President: E. F. Osborn, The Pennsylvania State University, University Park, Pennsylvania
Vice-President: Ian Campbell, State Division of Mines, San Francisco, California.
Secretary: George Switzer, U. S. National Museum, Washington, D. C.
Treasurer: Marjorie Hooker, U. S. Geological Survey, Washington, D. C.
Councilors: (1961–1963) Robert M. Garrels, Harvard University, Cambridge, Massachusetts.
O. F. Tuttle, The Pennsylvania State University, University Park, Pennsylvania.

According to the provisions of the Constitution, the following have been elected to fellowship:

John W. Adams, U. S. Geological Survey, Denver, Colorado.
George Baker, C.S.I.R.O., University of Melbourne, Parkville N. 2., Victoria, Australia.
Fernand A. J. Blondel, 18 rue Leonardo da Vince, Paris, France.
Esther W. Claffy, Naval Research Laboratory, Washington, D. C.
Robert G. Coleman, U. S. Geological Survey, Menlo Park, California.
William A. Deer, The University, Manchester, England.
Reynolds M. Denning, The University of Michigan, Ann Arbor, Michigan.
F. Donald Eckelmann, Brown University, Providence, Rhode Island.
Judith Weiss Frondel, 20 Beatrice Circle, Belmont, Massachusetts.
José M. Fuster, Museo Nacional Ciencias Naturales, Madrid, Spain.
William S. Fyfe, University of California, Berkeley, California.
John C. Hathaway, U. S. Geological Survey, Denver, Colorado.
Norman Herz, U. S. Geological Survey, A.P.O. 676, New York, N Y.
Allen Van Heyl, Jr., U. S. Geological Survey, Washington, D. C.
Sven Hjelmqyist, The University, Lund, Sweden.
Floyd A. Hummel, The Pennsylvania State University, University Park, Pennsylvania.
Horst H. Kedesdy, Signal Research and Development Laboratory, Fort Monmouth, New Jersey.
Arthur W. G. Kingsbury, University Museum, Oxford, England.

Jack A. Kohn, Signal Research and Development Laboratory, Fort Monmouth, New Jersey.
James F. McAllister, U. S. Geological Survey, Menlo Park, California.
James L. McAtee, Jr., Baylor University, Waco, Texas.
*Graham S. MacKenzie, University of New Brunswick, Fredericton, New Brunswick. Canada.
Robert C. Mackenzie, Macaulay Institute for Soil Research, Aberdeen, Scotland.
Henry G. Midgley, Building Research Station, Harpenden Herts, England.
Louis Moyd, 136 Park Ave., Yonkers, New York.
Kaarlo J. Neuvonen, University of Turku, Turku, Finland.
Ernest H. Nickel, Department of Mines and Technical Surveys, Ottawa, Canada.
Ronald W. B. Nurse, Building Research Station, Harpenden, Herts, England.
Ke'ichi Omori, Tohoku University, Sendai, Japan.
Fred D. Ordway, Jr., National Bureau of Standards, Washington, D. C.
James Phemister, 19 Grange Terrace, Edinburgh, Scotland.
Alan T. Prince, Department of Mines and Technical Surveys, Ottawa, Canada.
Donald H. Richter, U. S. Geological Survey, Hawaii National Park, Hawaii.
George R. Rigby, Canadian Refractories, Ltd., Grenville, Quebec, Canada.
Gershon D. Robinson, U. S. Geological Survey, Denver, Colorado.
Harold P. Rooksby, The General Electric Company, Ltd., Wembley, Middlesex, England.
Chalmer J. Roy, Iowa State University, Ames, Iowa.
Edgar R. Segnit, C.S.I.R.O., Highett, Victoria, Australia.
Thomas W. Stern, U. S. Geological Survey, Washington, D. C.
Lorin R. Stieff, U. S. Geological Survey, Washington, D. C.
William Uytenbogaardt, Free University, Amsterdam, Netherlands.
John S. Vhay, U. S. Geological Survey, Spokane, Washington.
Ewart A. Vincent, University Museum, Oxford, England.
Oleg von Knorring, The University, Leeds, England.
Charlotte M. Warshaw, The Pennsylvania State University (3703 Stewart Drive, Chevy Chase, Maryland).
James White, University of Sheffield, Sheffield, England.
Ray E. Wilcox, U. S. Geological Survey, Denver, Colorado.
Allan F. Wilson, University of Queensland, St. Lucia, Brisbane, Australia.

* Deceased

CHANGE IN BY-LAWS

A proposed change in Article II of the By-Laws was passed by a vote of 640 for and 138 against. Article II of the By-Laws now stands as follows:

Article II—Dues

Section 1. The annual dues for members and fellows shall be eight dollars ($8) payable in January. Members who are students shall pay one-half the dues of other members.

Section 2. No person shall be accepted as a fellow of the Mineralogical Society of America unless he pays dues for the year within three months after notification of his election.

MEMBERSHIP STATISTICS

The membership of the society continues to grow, as shown in the following table:

November 1, 1960

	1958	1959	1960
Honorary Fellows	0	3	4
Fellows	360	376	419
Members	1,185	1,501	1,623
	1,545	1,880	2,046

During 1960 the society lost through death eight Fellows: Harold L. Alling, Ciro Andreatta, Harold E. Buckley, Burnham S. Colburn, Austin B. Edwards, Guerdon S. Holden, John T. Lonsdale, and Graham S. MacKenzie.

Respectfully submitted,
GEORGE SWITZER, *Secretary*

REPORT OF THE TREASURER FOR 1960

(Year ending July 31, 1960)

To the Council of the Mineralogical Society of America:

SUMMARY STATEMENT

Cash on hand, August 1, 1959	$ 1,931.15	
Receipts, August 1, 1959–July 31, 1960	43,567.02	
Total	$ 45,498.17	$ 45,498.17
Disbursements, August 1, 1959–July 31, 1960	$ 34,924.09	
Transfer to capital	3,515.79	
Cash on hand, July 31, 1960	7,058.29	
Total	$ 45,498.17	45,498.17
Assets, July 31, 1960		
Cash on hand (as shown above)	$ 7,058.29	
Capital: Securities (market value)	151,285.00	
Endowment Fund cash	403.50	
Total	$158,746.79	158,746.79

RECEIPTS

Dues		
Fellows	$ 1,546.14	
Members	6,875.52	$ 8,421.66
Publications		
Geological Society of America grant	8,000.00	
Subscriptions to *American Mineralogist*	7,655.80	
Sale of reprints	3,285.78	
Sale of back numbers	2,706.87	
Sale of Index, vols. 31–40	852.00	
vols. 21–30	336.40	
vols. 1–20	176.20	
Advertising	1,779.13	
Mailing list	80.24	24,872.42
Endowment Fund		
Dividends and interest	7,214.61	
Fifty-Plus Committee	2,520.00	
Contributions	225.00	
Life Memberships	200.00	10,159.61
Special Funds		
Museum Fund	100.00	100.00
Exchange credits and collections	13.33	13.33
Total receipts		$43,567.02

DISBURSEMENTS

Honoraria		
Secretary (August 1, 1958–July 31, 1960)	$ 750.00	
Treasurer (November 15, 1958–July 31, 1960)	677.09	
Editor (April 1, 1959–March 31, 1960)	750.00	$ 2,177.09
Publications		
American Mineralogist (July 1959–April 1960)	22,616.03	
Reprints	3,570.40	
Program and abstracts	591.36	
Microtext of out-of-print issues	348.04	
Purchase of out-of-print issues	105.00	
National Science Foundation refund on index sales, May 1959–April 1960	744.50	
Postage and express	444.01	
Assistance	153.55	
Supplies	71.77	
Mailing list charge	26.37	
Subscription refunds	23.30	28,694.33

Office Expense		
Secretarial and clerical assistance	$ 895.40	
Officers' travel	48.00	
Printing	1,102.88	
Supplies	431.85	
Postage	705.04	
Telephone and telegrams	25.57	$ 3,208.74
International Mineralogical Association, 1960–61	150.00	
American Geological Institute, 1959–60	500.00	650.00
Roebling Medal (1959)	151.63	
MSA Award certificate	9.00	160.63
Checks returned	33.30	33.30
Total disbursements		$34,924.09

ENDOWMENT FUND

Amount	Security	Cost	Value[1]	Income[2]
	Bonds			
6M	Atlantic Coast Line, 4½	$ 5,257.50	$ 5,985	270.00
5M	New York Central, 5	4,300.00	3,438	250.00
5M	Southern Railway, 5	5,743.75	5,200	250.00
		$ 15,301.25	$ 14,623	$ 770.00
	Preferred stocks			
150	Fairbanks Whitney	$ 4,487.50	$ 3,431	$ 480.00[3]
60	Jones and Laughlin, A5	4,987.50	5,820	300.00
40	Potomac Electric Power, 2.44	2,000.00	1,940	97.60
200	Southern California Edison, 4.88	5,250.00	5,000	244.00
500	Union Pacific, 4	4,570.25	4,063	200.00
55	United States Steel, 7	6,946.20	7,865	385.00
50	Virginia Electric Power Co., 5	5,942.50	5,138	250.00
		$ 34,183.95	$ 33,257	$1,956.60

[1] Approximate market value, July 31, 1960.

[2] Fiscal year ending July 31, 1960, except where noted.

[3] Includes accumulated dividend.

	Common Stocks			
249	American Telephone and Telegraph	$ 11,255.98	$ 22,380	$ 821.72
50	Boston Insurance	1,500.00	1,694	90.00
100	Buckeye Steel Castings	3,800.00	2,675	150.00
177	Chase Manhattan Bank	11,281.25	10,797	181.20[4]
50	Chesapeake and Ohio Railway	2,368.75	2,944	200.00
300	Columbia Gas	5,174.72	5,963	265.00[5]
100	Columbus and Southern Ohio	2,087.50	4,725	165.00
150	Denison Mines, Ltd.	3,096.00	1,418	134.51
180	Diana Stores	2,800.30	3,150	180.00
210	Greyhound Corporation	2,300.00	4,645	210.00
261	Kroger Company	2,034.03	8,287	274.07
50	Phelps Dodge Corporation	1,975.00	2,425	150.00
100	Pittsburgh and West Virginia	2,787.50	1,238	—
100	Plymouth Cordage	4,750.00	5,750	290.00
350	Potomac Electric Power Co.	5,066.73	10,500	451.50
50	Public Service Electric and Gas	1,586.40	2,000	90.00
—	Sinclair Oil Corporation	—	—	150.00[6]
100	Southern Natural Gas	3,600.00	3,688	200.00
50	Spencer Kellogg	1,258.33	757	40.00
175	Standard Oil of New Jersey	1,761.65	7,131	393.75
60	United Fruit	3,067.50	1,238	15.00[7]
—	U. S. Playing Card	—	—	30.00[8]
	Merrill Lynch (interest)			6.26
		$ 73,551.64	$103,405	$4,488.01
	Total	$123,036.84	$151,285	$7,214.61
	Cash balance, Endowment Fund account, Riggs National Bank			403.50

[4] Additional shares purchased December 1959 and July 1960.

[5] Additional shares purchased December 1959.

[6] August 1959–July 1960. Sold in July 1960.

[7] One quarter dividend only.

[8] One quarter dividend. Sold in October 1959.

The summary statement and tables of figures show that the financial standing of the society has shown progress during the year and is satisfactory at the present time. We are faced, however, with several situations which bear directly on both our income and expenditures, and the solutions of some of these are not immediately evident. The comments that follow will elaborate the figures in the tables and relate them to the circumstances as they affect both our present and future position.

Income and Expense

The income is derived from three principal sources, either directly or from activity concerned with them.

Source	Amount	Per Cent 1959–60	Per Cent 1958–59
Dues	$ 8,421.66	19.4	18.2
Publication program	24,872.42	57.2	56.2
Endowment Fund	10,159.61	23.4	25.6

The percentages of income from these sources remain substantially the same as the previous year. The amount received in dues is $1000.00 more than last year, reflecting the continued rise in membership. The total agrees very well with the amount to be expected from a membership of 2000. The income from various parts of the publication program is apportioned about the same as last year. About 30% is derived from the sale of subscriptions to *The American Mineralogist*, amounting this year to $7655.80. At the present time, 1325 copies are distributed on a paid subscription basis; 517 are despatched within the United States to all fifty states and Puerto Rico; the other 808 are sent to 76 foreign countries. The figure for reprints, although larger this year, is only an apparent increase resulting from the distribution of payments in relation to the fiscal year. The income from the sale of indexes shows a 23% gain over last year. The figure for advertising represents income for more than one year due to a change in the method of invoicing; the portion for 1959–60 is larger due to an increase in both the amount of advertising and the rates. The total income from the Endowment Fund is of the same order as last year and will be discussed separately.

Expenditures are grouped as follows:

Item	Amount	Per Cent 1959–60	Per Cent 1958–59
Officers' honoraria	$ 2,177.09	6.2	3.2
Office expense	3,208.74	9.2	8.9
Publication program	28,694.33	82.3	85.3
Support of other organizations, etc.	810.63	2.3	2.6

The percentages of expenditures are also substantially the same as last year. Publication and related expense make up by far the major portion, with the printing and distribution of *The American Mineralogist* as the largest single item. Note should be made that the amount shown for this item at the close of the fiscal year covers only five issues; normal cost for six issues is approximately $27,000. The figure for officer's honoraria is higher than normally for it includes two years' payments to the Secretary and Treasurer as well as an increase in stipends. Office expense has remained at the same level in spite of increased business in the offices of the Editor, Secretary, and Treasurer. Of the unusually high amount for supplies, about 80% can be charged to the purchase of new record cards for the Treasurer's office for the decade 1961–70, an item recurring each ten years.

Endowment Fund

The book value of the Endowment Fund securities was $123,036.84 on July 31, 1960.

Of this amount, 12.4% is in bonds, 27.8% in preferred stocks, and 59.8% in common stocks. The market value, computed on July 31, 1960, was $151,285.00. Funds invested during the year have been derived chiefly from payments on Fifty-Plus Committee pledges (see *The American Mineralogist*, May–June, 1960, pages 747–748, for statement and list of names). Dividends and interest accruing from the securities totaled $7214.61 and exceeded the estimated income of $6850 chiefly as a result of payment of accumulated dividends by the Fairbanks Whitney Corporation. From securities now held, an income of $7200 is estimated for 1960–1961. The percentage yield of the portfolio, and of each type of security, at both book and market values, is given below. These compare favorably with the current 3.4% average yield from industrial common stocks and the 4.6% average return on corporate bonds as reported by Merrill Lynch in August 1960.

YIELD

	Total	Bonds	Preferred stock	Common stock
Book value	5.86	5.03	5.72	6.09
Market value	4.76	5.26	5.88	4.33

Mineralogical Abstracts

During 1959, the first year of co-publication of *Mineralogical Abstracts*, volume 14, numbers 1–4, was issued quarterly under the capable editorship of James Phemister. Copies were distributed to 683 members of the British society, 265 members of our society (in addition to about 260 who are members of the British society), and approximately 400 library subscribers. Total income from all 1959 subscriptions was about $6400.00 and the total cost of publication was about $11,400.00. Taking into account the initial joint contribution of $2800.00 (of which $500 had been used in 1958), that part of 1959 expense not covered by income amounted to $2700.00 ($1350 each society). In order to make *Mineralogical Abstracts* self-supporting, steps have been taken to reduce publication costs and to increase the income from subscriptions. These have resulted in some savings in cost, in spite of a 5% printer's increase as of January 1960, and enough of an increase in subscription revenue to make the overall picture for 1960 more assuring.

Income-Expenditure Outlook

It almost goes without saying that we are in the midst of a period of rising costs and that we must accept and resolve this fact. Our printing contract with George Banta Company, Inc. was rewritten this year to include a 6% increase to meet the higher cost of labor. Increases in membership and subscriptions, while admittedly desirable, bring with them increased expense, and we have had a net gain of 33% in the past 18 months. The Geological Society of America, in line with intentions outlined in November 1958, has found it necessary to initiate a schedule for the gradual decrease over a five-year period and termination in 1965 of our annual grant of $8000, given to us as an affiliated society to assist in publication of *The American Mineralogist.*

To maintain our ability to continue publication of *The American Mineralogist* and *Mineralogical Abstracts* at the present high standard, the Council has taken several actions. It has recommended that the membership approve an increase in dues for both fellows and members. It has approved the advance of the subscription price of *The American Mineralogist* to an annual rate of $10.00. In November 1959, it appointed an Advertising Manager to solicit more advertising for the *Journal.* Your Treasurer has also explored several smaller avenues for reducing costs and supplementing income. A postal permit, allowing special rates for domestic mailing, was secured this year. The schedule of reprint charges has been revised in line with our new printing contract. The strip announcement distributed with the annual dues bill has been responsible for the increased sale of indexes reported in the past two years. A comparable strip, sent to subscribers, has had a similar response with respect to index sales and has increased the number of subscriptions to *Mineralogical Abstracts*. A complete set of *The American Mineralogist,* with all out-of-print numbers, is now offered for sale. Other possible sources of income are being considered and the Treasurer will welcome suggestions from the membership.

During the past year, the Mineralogical Society of America received notification from the Internal Revenue Service of tax-exempt status as an educational and scientific organization. Contributions and bequests to the society are therefore deductible items under the provisions of the Internal Revenue Code. The society was also notified by the Commissioners of Inland Revenue (Great Britain) that it had been placed on the list of societies approved for purposes of tax deductions by British members.

The Treasurer's office depends on several individuals for continuity of operation and I should like to place on record here my warm thanks to Catherine Skinner, for her able assistance with the records; Edward P. Henderson, Samuel S. Goldich, and Arthur Montgomery, of the Finance Committee, for their cooperation and competent advice; Stanly Carr and Herbert Allen, of Merrill Lynch, custodian of our securities; Irwin H. Wensink and Alvin A. Lang, of George Banta Company, Inc., printer of *Th American Mineralogist*. And to those members of the society who have responded generously when called on for advice and assistance, a special thank you and my appreciation.

Respectfully submitted,
MARJORIE HOOKER, *Treasurer*

REPORT OF THE AUDITING COMMITTEE

To the President of the Mineralogical Society of America:

The Auditing Committee has examined and verified the accounts of the Treasurer of the Mineralogical Society of America for the fiscal year beginning August 1, 1959 and ending July 31, 1960. It is the Committee's opinion that the Treasurer has done an excellent job, and she should be commended for the admirable manner in which she has kept the Society's books.

Respectfully submitted,
MARIE L. LINDBERG
ALVIN VAN VALKENBURG
GUNNAR KULLERUD, *Chairman*

REPORT OF THE EDITOR FOR 1960

The 1960 volume of *The American Mineralogist* contained 1343 pages, very close to that of 1959, in both size and number of articles. There were 74 major and 65 shorter articles. The authors represented 28 U. S. educational institutions, 9 Federal agencies, and 11 private or industrial laboratories, 15 foreign educational institutions and 6 laboratories, giving a total of 69 institutions. Seven new minerals were described. There were 21 book reviews, and 72 items under Dr. Fleischer's valuable section on New Mineral Names.

The editor is grateful to the associate editors, and to many other individuals who have read manuscripts, and reported on them as to their suitability for *The American Mineralogist*. Likewise, the editor wishes to express his appreciation to the publisher of our *Journal*, George Banta Company, Inc. Their printing skill is evidenced by the excellent appearance of the *Journal*, and their splendid cooperation makes the editorial task much easier.

A summary of the contents of Vol. 45 is given in the following table.

Distribution of Subject Matter in Vol. 45

Subjects	Number	Pages		% of Total
Leading articles	74	949		76.0
Short articles	65	211		16.8
			1,160	
Memorials	2	8		
Awards	2	11		
Society proceedings	1	21		
			40	3.2
Book Reviews	21	13		
New Mineral Names	72	31		
Notes	20	7		
			51	4.0
Total			1,251	100.0
Membership list			66	
Index, Title Page, Table of Contents			26	
Grand Total			1,343	

Respectfully submitted,
Lewis S. Ramsdell, *Editor*

LIST OF FORMER OFFICERS AND MEETING PLACES

By recommendation of the Council, a complete list of past officers is printed in the pro eedings of the annual meeting of the Society:

Honorary Presidents

Edward S. Dana	1925–1935
Charles Palache	1949–1954
Edward H. Kraus	1955–

Presidents		Vice-Presidents	
920	Edward H. Kraus	1920	Thomas L. Walker
921	Charles Palache	1921	Waldemar T. Schaller
922	Thomas L. Walker	1922	Frederick A. Canfield
923	Edgar T. Wherry	1923	George F. Kunz

PRESIDENTS (*Cont.*)

1924	Henry S. Washington
1925	Arthur S. Eakle
1926	Waldemar T. Schaller
1927	Austin F. Rogers
1928	Esper S. Larsen
1929	Arthur L. Parsons
1930	Herbert E. Merwin
1931	Alexander H. Phillips
1932	Alexander N. Winchell
1933	Herbert P. Whitlock
1934	John E. Wolff
1935	Clarence S. Ross
1936	William S. Bayley
1937	Norman L. Bowen
1938	Ellis Thomson
1939	Max N. Short
1940	William F. Foshag
1941	Frederick E. Wright
1942	Arthur F. Buddington
1943	John F. Schairer
1944	R. C. Emmons
1945	Kenneth K. Landes
1946	Paul F. Kerr
1947	M. J. Buerger
1948	M. A. Peacock
1949	John W. Gruner
1950	George Tunell
1951	A. Pabst
1952	Michael Fleischer
1953	J. D. H. Donnay
1954	Sterling B. Hendricks
1955	Harry H. Hess
1956	Clifford Frondel
1957	D. Jerome Fisher
1958	George E. Goodspeed
1959	Ralph F. Grim
1960	Joseph Murdoch

VICE-PRESIDENTS (*Cont.*)

1924	Washington A. Roebling
1925	Herbert P. Whitlock
1926	George Vaux, Jr.
1927	George L. English
1928	Lazard Cahn
1929	Edward Wigglesworth
1930	John E. Wolff
1931	William F. Foshag
1932	Joseph L. Gillson
1933	Frank B. Guild
1934	William A. Tarr
1935	Ellis Thomson
1936	Harold L. Alling
1937	H. V. Ellsworth
1938	Kenneth K. Landes
1939	Burnham S. Colburn
1940	Ian Campbell
1941	William J. McCaughey
1942	Martin J. Buerger
1943	John W. Gruner
1944	Harry Berman
1945	George Tunell
1946	S. B. Hendricks
1947	Carl Tolman
1948	Adolf Pabst
1949	J. D. H. Donnay
1950	Ralph E. Grim
1951	Michael Fleischer
1952	J. D. H. Donnay
1953	Sterling B. Hendricks
1954	Harry H. Hess
1955	Clifford Frondel
1956	D. Jerome Fisher
1957	George E. Goodspeed
1958	Ralph E. Grim
1959	Joseph Murdoch
1960	E. F. Osborn

SECRETARIES

1920–1922	Herbert P. Whitlock
1923–1933	Frank R. Van Horn
1933–1934	Albert P. Peck
1934–1944	Paul F. Kerry
1944–1959	C. S. Hurlbut, Jr.
1959–	George Switzer

TREASURERS

1920–1923	Albert B. Peck
1924–1929	Alexander H. Phillips
1929–1930	Albert B. Peck
1930–1940	Waldemar T. Schaller
1941–1958	Earl Ingerson
1958–	Marjorie Hooker

EDITORS

1920–1921	Edgar T. Wherry
1922–1956	Walter F. Hunt
1957—	Lewis S. Ramsdell

Councilors

1920 Arthur S. Eakle, Frank R. Van Horn, Fred E. Wright, Alexander H. Phillips.
1921 Frank R. Van Horn, Fred E. Wright, Alexander H. Phillips, Austin F. Rogers.
1922 Fred E. Wright, Alexander H. Phillips, Austin F. Rogers, Thomas L. Watson.
1923 Alexander H. Phillips, Austin F. Rogers, Thomas L. Watson, Esper S. Larsen.
1924 Austin F. Rogers, Thomas L. Watson, Esper S. Larsen, Arthur L. Parsons.
1925 Thomas L. Watson, Esper S. Larsen, Arthur L. Parsons, William F. Foshag.
1926 Esper S. Larsen, Arthur L. Parsons, William F. Foshag, William A. Tarr.
1927 Arthur L. Parsons, William F. Foshag, William A. Tarr, Alexander N. Winchell.
1928 William F. Foshag, William A. Tarr, Alexander N. Winchell, Ellis Thomson.
1929 William A. Tarr, Alexander N. Winchell, Ellis Thomson, Clarence S. Ross.
1930 Alexander N. Winchell, Ellis Thomson, Clarence S. Ross, Paul F. Kerr.
1931 Ellis Thomson, Clarence S. Ross, Paul F. Kerr, William S. Bayley.
1932 Clarence S. Ross, Paul F. Kerr, William S. Bayley, William M. McCaughey.
1933 Paul F. Kerr, William S. Bayley, William J. McCaughey, Kenneth K. Landes.
1934 William S. Bayley, William J. McCaughey, Kenneth K. Landes, E. P. Henderson.
1935 William J. McCaughey, Kenneth K. Landes, E. P. Henderson, J. F. Schaierer.
1936 Kenneth K. Landes, E. P. Henderson, J. F. Schairer, Arthur F. Buddington.
1937 E. P. Henderson, J. F. Schairer, Arthur F. Buddington, Arthur P. Honess.
1938 J. F. Schairer, Arthur F. Buddington, Arthur P. Honess, R. C. Emmons.
1939 Arthur F. Buddington, Arthur P. Honess, R. C. Emmons, Carl Tolman.
1940 Arthur P. Honess, R. C. Emmons, Carl Tolman, D. Jerome Fisher.
1941 R. C. Emmons, Carl Tolman, D. Jerome Fisher, Martin A. Peacock.
1942 Carl Tolman, D. Jerome Fisher, Martin A. Peacock, Adolf Pabst.
1943 D. Jerome Fisher, Martin A. Peacock, Adolf Pabst, C. S. Hurlbut, Jr.
1944 Martin A. Peacock, Adolf Pabst, Michiel Fleischer, S. J. Shand.
1945 Adolf Pabst, Michael Fleischer, S. J. Shand, R. E. Grim.
1946 Michael Fleischer, S. J. Shand, R. E. Grim, Joseph Murdoch.
1947 S. J. Shand, R. E. Grim, Joseph Murdoch, H. H. Hess.
1948 R. E. Grim, Joseph Murdoch, H. H. Hess, Clifford Frondel.
1949 Joseph Murdoch, H. H. Hess, Clifford Frondel, Lewis S. Ramsdell.
1950 H. H. Hess, Clifford Frondel, Lewis S. Ramsdell, E. F. Osborn.
1951 Clifford Frondel, Lewis S. Ramsdell, E. F. Osborn, George T. Faust.
1952 Lewis S. Ramsdell, E. F. Osborn, George T. Faust, Victor T. Allen.
1953 E. F. Osborn, George T. Faust, Victor T. Allen, C. Osborn Hutton.
1954 George T. Faust, Victor T. Allen, C. Osborne Hutton, Felix Chayes.
1955 Victor T. Allen, C. Osborne Hutton, Felix Chayes, L. G. Berry.
1956 C. Osborne Hutton, Felix Chayes, L. G. Berry, C. B. Slawson, A. O. Woodford.
1957 Felix Chayes, L. G. Berry, C. B. Slawson, A. O. Woodford, S. S. Goldich.
1958 L. G. Berry, C. B. Slawson, A. O. Woodford, S. S. Goldich, B. H. Mason, R. H. Jahns, C. Milton.
1959 S. S. Goldich, B. H. Mason, R. H. Jahns, C. Milton, W. R. Foster, E. W. Nuffield.
1960 R. H. Jahns, C. Milton, W. R. Foster, E. W. Nuffield, J. R. Goldsmith, Horace Winchell

Annual Meeting Places

1920 Chicago, Illinois
1921 Amherst, Massachusetts
1922 Ann Arbor, Michigan
1923 Washington, D. C.
1924 Ithaca, New York
1925 New Haven, Connecticut

ANNUAL MEETING PLACES (*Cont.*)

1926 Madison, Wisconsin
1927 Cleveland, Ohio
1928 New York, N. Y.
1929 Washington, D. C.
1930 Toronto, Canada
1931 Tulsa, Oklahoma
1932 Cambridge, Massachusetts
1933 Chicago, Illinois
1934 Rochester, New York
1935 New York, N. Y.
1936 Cincinnati, Ohio
1937 Washington, D. C.
1938 New York, N. Y.
1939 Minneapolis, Minnesota
1940 Austin, Texas
1941 Boston, Massachusetts
1942 No meeting held
1943 No meeting held
1944 No meeting held
1945 Pittsburgh, Pennsylvania
1946 Chicago, Illinois
1947 Ottawa, Canada
1948 New York, N. Y.
1949 El Paso, Texas
1950 Washington, D. C.
1951 Detroit, Michigan
1952 Boston, Massachusetts
1953 Toronto, Canada
1954 Los Angeles, California
1955 New Orleans, Louisiana
1956 Minneapolis, Minnesota
1957 Atlantic City, New Jersey
1958 St. Louis, Missouri
1959 Pittsburgh, Pennsylvania
1960 Denver, Colorado

Recipients of the Roebling Medal

1937 Charles Palache
1938 Waldemar T. Schaller
1940 Leonard James Spencer
1941 Esper S. Larsen, Jr.
1945 Edward H. Kraus
1946 Charence S. Ross
1947 Paul Niggli
1948 William Lawrence Bragg
1949 Herbert E. Merwin
1950 Norman L. Bowen
1952 Fred E. Wright
1953 William F. Foshag
1954 Cecil Edgar Tilley
1955 Alexander N. Winchell
1956 Arthur F. Buddington
1957 Walter F. Hunt
1958 Martin J. Buerger
1959 Felix Machatschki
1960 Tom. F. W. Barth

Recipients of the Mineralogical Society of American Award

1951 Orville F. Tuttle
1952 Frederick H. Stewart
1953 L. H. Ahrens
1954 Hatten S. Yoder, Jr.
1955 Julian R. Goldsmith
1956 George C. Kennedy
1957 Rustum Roy
1958 Charles E. Weaver
1959 Harry F. W. Taylor
1960 Donald L. Graf

1960 ANNUAL MEETING AT DENVER, COLORADO

The meetings of the following societies were held on October 30–November 2, 1960.

The Geological Society of America—73rd
The Paleontological Society—52nd
The Mineralogical Society of America—41st
Society of Economic Geologists—41st
The Geochemical Society—5th

Abstracts of the papers presented are printed in the Bulletin of the Geological Society of America, Vol. 71, Number 12, Part 2, pp. 1811–2010.

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Epidote—solid green massive (California)
Actinolite—coarse green crystallized masses (California)

35¢ per lb.
Anorthite—cleavages in hornblende norite (California)
Oolitic hematite—reddish pisolitic masses (New York)
Magnetite—black massive, no polarity (California)

50¢ per lb.
Psilomelane—black massive, some reniform (New Mexico)
Burkeite—buff crystalline masses (California)
Glauconite—dark green cementing sandstone (Texas)

55¢ per lb.
Knotted schist—shows incipient porphyroblasts (California)
Bishop tuff—an unwelded tuff (California)
Campito sandstone—magnetite-rich arkosic sandstone (California)
Peridotite—"Kimberlite" (Arkansas)
Olivine peridotite—"Dunite" (No. Carolina)

75¢ per lb.
Galena—good quality cleavable and cleavages (Tri-State)
Tremolite—coarse radiating silky masses, some rock (Utah)
Oligoclase—white to brown-stained, striated. Ratio AB_{85} : AN_{15} (New York)

$1.00 per lb.
Clinozoisite—yellow-green granular, with quartz, mica (Oregon)
Nephrite—grey-green crystalline masses (California)

$2.00 per lb.
Cinnabar—blood-red cleavages scattered on quartzite (Nevada)
Turquois—blue masses in rock (Arizona)

$2.25 per lb.
Smaltite—tin white metallic, very rich, with other arsenides (Canada)
Tyuyamunite—bright yellow encrustations on limestone (New Mexico)

$5.00 per lb.
Jamesonite—grey metallic in quartz, with scheelite. (Idaho)

$7.50 per lb.
Bismuthinite—rich grey metallic (Ariozna-Colorado)
Melanocerite—brown to black masses in calcite, etc. (Canada)

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OTHER RECENT ACQUISITIONS

Alvite. Norway. Brown massive piece with unusual gel structure 3 x 5″, $35.00

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Dioptase. French Congo. Bright emerald green crystal groups 1 x 2″, $15.00; 2 x 2″, $30.00; 3 x 3″, $150.00

Gold. New Zealand. A polished slice of quartz rich in native gold 1¼ x 1⅝″, $45.00

Hibonite. Madagascar. Black crystalline with blue-gray corundum 4½ x 6″, $35.00; black crystals in rock 3 x 3½″, $35.00

Ilmenite. Norway. Very large crystals 2 x 2½″, $20.00; 3½ x 4″, $25.00; large crystals on rock 2 x 3″, $20.00; 3 x 4″, $27.50

Kasolite. New York (first reported occurrence in the state). Straw yellow pseudomorphs after small uraninite crystals in pegmatite with uranophane, allanite, etc. 3 x 4″, $10.00; 4 x 5″, $15.00

Nigerite. Nigeria. Minute crystals on rock 2 x 3″, $20.00

Miargyrite. Bolivia. Crystalline mass with native silver 2 x 2½″, $25.00 each.

Spinel. Madagascar. Large black octahedral crystals 2 x 2″, $15.00; crystal clusters with calcite 3 x 4″, $15.00

Spinel. Ferrian (Pleonaste). Queensland. Black waterworn nuggets averaging half inch. $12.00 per ounce.

Ullmannite. Arsenian (Corynite). Austria. Crystalline mass with siderite 2 x 3″, $10.00

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